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The Mystery of β Lyrae

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AT the dedication ceremony of the Yerkes Observatory, on October 21, 1897, scientific men gathered from all parts of the world to listen to a review of current results in astronomy and astrophysics; and, among the speakers, was the professor of theoretical astronomy at the University of Illinois, Dr. G. W. Myers, who spoke on the subject, "The System of β Lyrae."[1] Therefore it was not an accident that, forty-three years later, at the opening of the new and magnificent addition to the Warner and Swasey Observatory of Case School of Applied Science, on October 25, 1940, the subject of my talk was also the mysterious star β Lyrae.

In recent years the study of stellar spectra has made much progress, and our understanding of various abnormal features, features which find no place within the regular sequence of the stars, has been greatly improved. During this time several of my colleagues and I have repeatedly attacked the problem of β Lyrae from various sides. But only during the past four or five months have we reached what we believe to be the correct and final interpretation of the major features of this star. This success has been due, very largely, to the important theoretical work of G. P. Kuiper, who has already announced his results at a recent meeting of the American Astronomical Society. Stimulated by the remarkable results of his dynamical theory I have re-examined the spectroscopic evidence, and this, in turn, has been useful for improving the theory. My purpose here is to give a simple résumé of the entire problem. If I have occasionally over-simplified the procedure, especially where the original work involved complicated mathematical developments, it is because the numerical results here presented are intended to be more in the nature of illustrations of how the work was done than for purposes of record.

I doubt whether any other star in the sky has presented so many difficult problems and has received so much attention from the astronomers as β Lyrae. It is a bright star, normally of the third magnitude, a few degrees south of the brilliant summer star Vega. It was known to the Arabs as Sheliak and to the ancient Chinese as Tsan Tae, but apparently not one of the ancient astronomers noticed that the light of β Lyrae is not constant, but undergoes periodic variations, fluctuating between the third and fourth stellar magnitudes. In 1784 John Goodricke, a deaf-mute resident of York, in England, scarcely twenty years of age, first noticed that on some nights β Lyrae appeared much fainter than the neighboring star γ Lyrae, whereas on other nights the two were almost alike. This led him to make regular observations and he soon established that every 6.5 days β Lyrae is faint,

[1] G. W. Myers, Astrophys. J. **7**, 1 (1898).

and at intermediate dates it is bright. Some years later Argelander, in Germany, also made extensive observations of β Lyrae and found that while one minimum is deep, so that the star is almost a whole magnitude fainter than normal, the following minimum is only half as deep, making the star about half a magnitude fainter than normal. He, therefore, concluded that the true cycle of events is exactly double that found by Goodricke, namely, $12^{d}\ 21^{h}\ 53^{m}\ 10^{s}$.

Since its discovery in 1784, β Lyrae has been observed by hundreds of astronomers. I remember, myself, having observed it on night duty in the trenches of the first World War. Fortunately, it is so bright that no telescope is required. It is tremendously fascinating to watch the light of this star change from night to night, and almost from hour to hour. The astronomical literature records more than 200 published investigations of this star. Several thousand spectrograms have been made at a dozen or more observatories. Tens of thousands of photographic or photometric observations have been secured, and there must be in the files of observatories hundreds of thousands of visual estimates of the light of this star. It is no exaggeration to say that about one million dollars has been spent during the past century and a half toward the solution of the problem of β Lyrae!

Progress has been slow, but it has been steady. There are few better examples of the true nature of scientific inquiry. Goodricke found that the brightness of β Lyrae varies, and Argelander determined its period. Several astronomers published theories intended to explain the observations. In 1866, Father Secchi, in Italy, noticed bright lines in the spectrum of β Lyrae, and Von Gothard in Hungary was struck with their unaccountable variations in visibility. In 1891 Mrs. Fleming at the Harvard Observatory discovered that there are also absorption lines, flanking the bright emission lines; and E. C. Pickering, also at Harvard, derived from the measured velocities of the absorption lines a velocity curve which could be interpreted in terms of orbital motion of a binary system.

The early theories of β Lyrae now have only historical interest. In a book published in 1822, John Bonnycastle wrote with regard to all the known variable stars:

> If the light of the sun and stars be owing to a combustion similar to that which is required to produce light in most other substances, it will follow that when the inflammable matter is decomposed, the ignition will cease; or if a mass of combustible matter begin by any cause to burn, its ignition and emission of light will commence at the same time. So that if these considerations be applied to fixed stars, the appearance of some and the disappearance of others, will be rationally accounted for.

We see here a perfectly logical attempt to explain stellar variability in terms of demand and supply of fuel. Ten or 20 years ago this theory probably sounded funnier than it does now. In recent years many astrophysical phenomena have found their explanation in terms of just such a "demand-and-supply" theory; only we no longer think of the fuel in stars as undergoing oxidation or some other simple chemical process. The fuel we now deal with is the energy concealed in the nuclei of atoms; and the transformation of elements releases the observed radiant energy of the stars.

But even though Bonnycastle's theory may have been logical, we know now that it does not explain the variation in the brightness of β Lyrae. There were other theories. One, which was proposed first in 1667 by Bouillaud in France, long before β Lyrae was observed by Goodricke, attributes stellar variability to the rotation of a star of unequal surface brightness. This interesting theory has cropped up many times in the past 300 years, and for some time it was believed to provide the correct explanation for β Lyrae. Later observations displaced it, and it remained in discard until a few years ago when astronomers began again to stress the probability that stars rotate on their axes—very much as the earth does. Although the rotational theory of Bouillaud never succeeded in explaining the major effects in β Lyrae, it is now an important subsidiary theory which helps us to understand certain minor effects.

Another Frenchman, Maupertuis—famous for his measurement of the size of the earth—proposed the idea that a variable star may not be exactly spherical, but flattened, as is a millstone, and that in rotating this flattened star may sometimes show us its broad side, and sometimes its narrow side. This would produce marked changes in the visible amount of light.

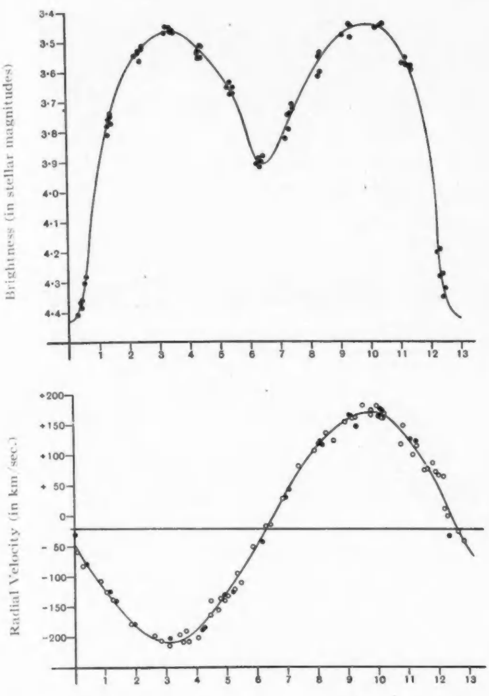

FIG. 1. Light curve (above) and velocity curve (below) of β Lyrae [according to Baxandall], plotted as functions of the time counted in days from the deepest point of the light curve.

Maupertuis' theory was severely criticized by Mädler, who pointed out that a rotating body should be flattened at the poles, as the earth and Jupiter are, and that a flattened body turning around its shorter axis will always be oriented in the same way; there would then be no change in light. Mädler's criticism is, of course, correct as far as it goes. But probably at the time of the discovery of β Lyrae's variability in light, and certainly soon afterward, most astronomers regarded Maupertuis' flattened stars as parts of binary systems, where the revolution of one flattened star around another star, not necessarily flattened, could very well result in a continuous change of orientation with consequent variation in brightness. We shall see that the millstone theory of Maupertuis, in a modern dress, helps to explain some of the minor phenomena which accompany the variation of β Lyrae.

In 1855 the French astronomer and physicist Arago, in a course of popular astronomical lectures in Paris, reviewed the existing theories of β Lyrae and suggested that the variation in light might be caused by partial obscuration of a bright star by cosmical clouds in its vicinity. He pointed out that the English astronomer, Hind, had suggested that most of the fainter variable stars are red, and at maximum light appear "surrounded with a kind of fog." Perhaps, thought Arago, the fog periodically covers the visible surface of β Lyrae and renders its light dimmer than usual. Strange as it may seem, this theory also returns in a new form and takes an important part in the process of disentangling the complicated problem of β Lyrae.

The most essential theory of β Lyrae is, of course, that of mutual eclipses of two components in a binary system. This idea, with regard to Algol-type variables, goes back to the astronomer Pigott. It provides the only obvious interpretation of those light curves that indicate constant brightness over a large part of the period, with two sharp interruptions, or drops in the brightness, corresponding to the two eclipses. But, in the case of β Lyrae, the light varies in a continuous manner; there is no constant phase at maximum. Hence it was not at once obvious that the eclipse theory could be applied to it.

However, from the displacements of the absorption lines measured at the Harvard Observatory, E. C. Pickering concluded that the component of motion of the bright star in the line of sight, when plotted as a function of the time, gives almost exactly a sine curve. This would be true if the star were revolving, in its period of nearly 13 days, in an almost circular orbit around the center of mass of a double-star system. In other words, β Lyrae is a spectroscopic binary, just like hundreds of other stars, and the double-star hypothesis which is good for the rest should also be good for β Lyrae.

Let us examine the evidence a little more closely. In Fig. 1 the light curve at the top and the velocity curve at the bottom are plotted as functions of the time, which is counted in days from the deepest point on the light curve. We notice that this deepest point occurs almost exactly at the time when the radial velocity changes from positive values to negative values. We must remember here that the constant, or

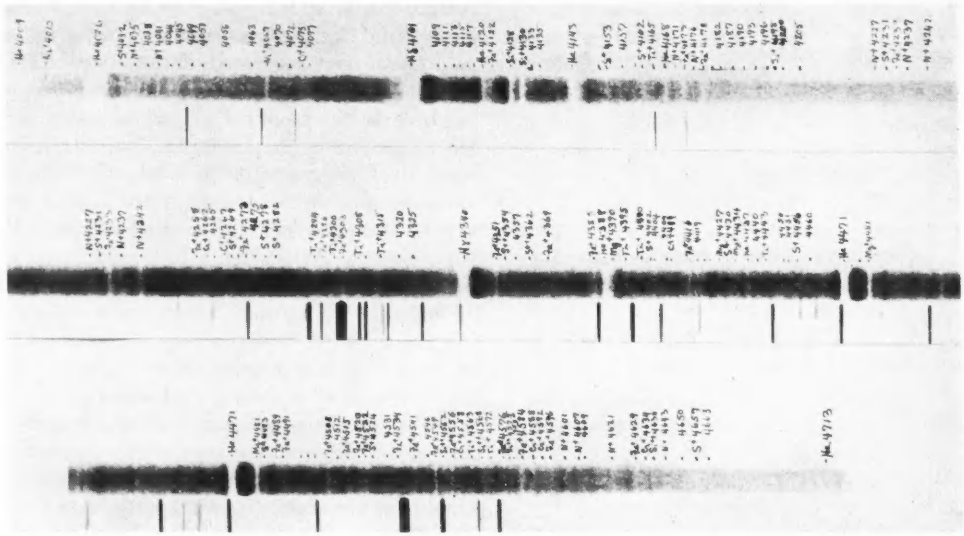

FIG. 2. Spectrum of β Lyrae 1.5 days after principal minimum. (This is a negative; the comparison lines belong to Ti and Fe.)

average, speed of β Lyrae relative to the solar system corresponds to 19 km/sec of approach. Now, as seen from the earth the bright star will cease receding and begin approaching when it is at the most distant point in its circular path around the center of mass. If there is another star in the system, and there must be in order to have binary motion produced, this secondary component will be at the nearest point of its orbit. If, moreover, the plane of the orbit of β Lyrae is oriented in the line of sight, or close to it, the secondary component will be in front of the primary and will eclipse it. The eclipse may be total, or annular (ring-shaped), or partial.

Six and one-half days later we observe the second, shallow minimum of light in β Lyrae. At the same moment the primary component ceases to approach us and begins to recede. At this point the primary is in front and the secondary is behind. We have again an eclipse, which may also be total, annular or partial. But if the principal eclipse is total then the secondary must be annular, and vice versa.

It looks, then, as though we are dealing with a pair of eclipses. But we must not be too hasty. The light curve is not constant between the two minimums, as it is in the case of Algol and of other eclipsing variable stars. Perhaps the two binary components are so close to each other, that one eclipse begins when the other ends. If the two surfaces were in contact this would, indeed, be the case and the difficulty would be removed. But we have as yet no way to prove that the stars are in contact, and we must study the question in more detail.

Perhaps the most fruitful approach is through a description of the spectrum. Figure 2 is a reproduction of a spectrogram secured at the Yerkes Observatory. The time is about a day and a half after principal eclipse. We observe strong emission lines of hydrogen and helium and a large number of absorption lines—all superposed on a strong continuous spectrum. The absorption lines of hydrogen and helium are very strong. Those of the ionized metals are weaker. If we had for comparison a spectrum of the star Rigel (β Orionis) we should find a great similarity to β Lyrae. We designate the spectrum of Rigel as B9, which is a symbol in an arbitrary classification of the spectra of the stars. The corresponding temperature at the surface of such a star is about 15,000°K. A day and a half from principal minimum the radial velocities of the two components of the double star are still quite similar, and the absorption lines of the two stars should not be resolved.

Hence we expect to see only one set of absorption lines. Figure 2 shows that this is actually the case.

The hydrogen and helium lines are deep and nearly devoid of hazy wings. Such wings occur always when the pressure within the atmosphere is relatively high, and this happens always when the star is a dwarf in size, somewhat like the sun. In the primary component of β Lyrae the pressure of the reversing layer, or atmosphere, must be low. We infer that the star is a supergiant.

Figure 3 shows another spectrum of β Lyrae, taken 9.5 days after one principal minimum, or 3.5 days before the next principal minimum. Notice that the strong absorption lines of hydrogen and helium are double. The ionized metals and the strong line Mg II 4481 are single and show a large displacement toward the red, indicating that the star was then receding at the rate of 160 km sec^{-1}. We infer that the red components of the double lines and all single lines belong to the same source, and it is clear that this spectrum is identical with that of the B9 star. The violet components of the double lines of hydrogen and helium belong to a new source, which was not separated from the B9 spectrum in Fig. 2, but which we see here very plainly.

The earlier spectroscopists designated this new spectrum as belonging to type B5 (or B2), because they thought that it resembled the spectrum of an ordinary star having this classification symbol. A large amount of confusion has resulted from this classification. As a matter of fact, no ordinary star has a spectrum resembling the secondary absorption spectrum of β Lyrae. The most significant departure of the secondary spectrum of β Lyrae from that of an ordinary early type star is the faintness of the line Mg II 4481. This line is fairly strong in all normal B-stars. Only in the O-stars (whose temperatures are of the order of 30,000°K) is it faint. Yet, the secondary spectrum of β Lyrae is not similar to class O, because other characteristic lines, such as Si IV, N III, are also missing. We must conclude that the secondary spectrum does not resemble that of any normal star. It contains essentially hydrogen and neutral helium, the lines of the latter being especially strong.

The faintness of Mg II 4481 is particularly intriguing, because the same phenomenon is also

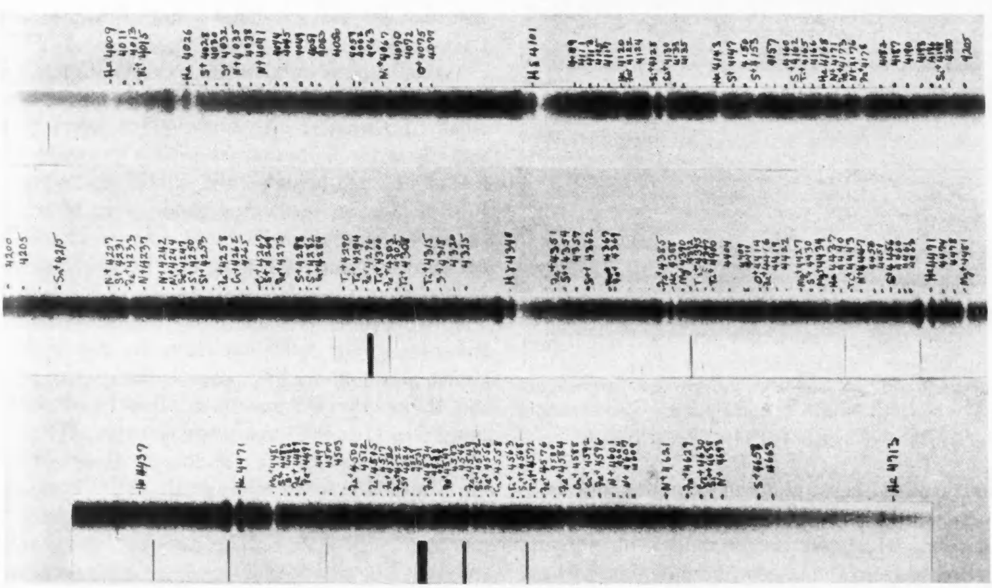

FIG. 3. Spectrum of β Lyrae 9.5 days after principal minimum.

observed in several other peculiar astronomical spectra. Several years ago I suggested that whenever the Mg II line is weak the lines 4128 and 4131A of Si II are also abnormally weak. Moreover, the effect occurs only in peculiar objects, never in normal stars. In a number of objects the faintness of Si II and Mg II is associated with an abnormal strengthening of the He I line 3965A and with a weakening of several other He I lines, notably 4388 and 4009A. Gradually the observed peculiarities begin to fit into a theory: all lines which are weakened in the peculiar objects originate from normal excited levels of the various atoms and these levels are connected with the ground level (or with other low lying levels) by means of strong transitions. Those lines which are strong, for example, 3965A of He I, and also the great majority of observable lines of Fe II, Ti II, Cr II, Ni II, and so forth, originate from lower metastable levels, which have no transitions downward.

Clearly the relative enhancement of lines from metastable levels represents a departure from

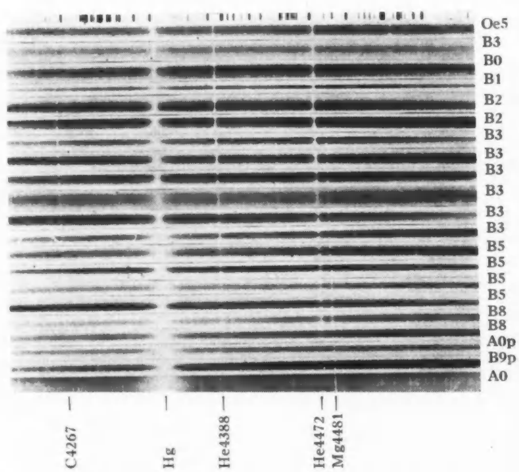

FIG. 4. Sequence of stellar spectra of class B.

conditions of thermodynamic equilibrium. It is interpreted as a result of dilution of the exciting radiation, which in astronomical phenomena must come from the photosphere of a star. Now, for thermodynamic equilibrium, the populations of the atoms in different excited states are determined by the Boltzmann formula,

$$N_i/N_1=(g_i/g_1)e^{-E_i/kT}, \tag{1}$$

where E_i is the excitation potential of level i, T is the temperature of the radiation, and g_1, g_i are the statistical weights of the two states. If the photosphere of the exciting star is at a considerable distance from the mass of gas, then the population of a metastable excited level is still determined by Eq. (1), while that of an ordinary excited level becomes

$$N_p/N_1=W(g_p/g_1)e^{-E_p/kT}. \tag{2}$$

The quantity W is called the *dilution factor*. It measures the ratio of the solid angle subtended by the disk of the star as seen from the point within the radiating gas which we are investigating to 4π. Obviously, $W=1$ corresponds to the case of thermodynamic equilibrium, because then the entire sphere, as seen from the gas, appears uniformly bright. In the case of a departure from thermodynamic equilibrium we must have $W<1$, and a good approximate formula is

$$W=R^2/4r^2, \tag{3}$$

where R is the radius of the star and r is the distance of the gas-mass under investigation from the center of the star.

We have seen that, in the secondary spectrum of β Lyrae, the Mg II line 4481A is abnormally weak. To answer the question of how much weaker it is, as compared with a normal star, let us look at the sequence of stellar spectra in Fig. 4. Here are collected the spectra of representative stars between temperature 25,000°K (at the top) and 10,000°K (at the bottom). As judged from the relative strengths of the helium and hydrogen lines, the secondary spectrum of β Lyrae would fall somewhere in the middle. Hence astronomers have usually designated it as the B2 or the B5 spectrum. But in all these stars Mg II 4481A is quite strong. We can readily measure the total energy absorbed by the Mg II line in an average B2 or B5 star and compare it with that measured in the secondary spectrum of β Lyrae. The ratio is between 10 and 100. Let us adopt 50.

Now, it would be hasty to conclude from this that W is 1/50, because we do not yet know

whether the absorbed energies of the lines in β Lyrae and in the stars are directly proportional to the numbers of atoms which are available in the different levels to produce the absorption. This is a complicated subject and leads into astrophysical considerations which are somewhat removed from the purpose of our discussion. At any rate, the problem has been investigated, and we have satisfied ourselves that, as a first approximation, the proportionality of absorbed energy to available number of atoms is satisfactory. Hence W is 0.02 and from Eq. (3) we compute

$$r = 3R. \tag{4}$$

This result is of crucial importance in the problem of β Lyrae. Its shows conclusively that the secondary spectrum is not produced by a normal stellar reversing layer—several hundreds or perhaps thousands of kilometers in height—but comes from a diffuse mass of gas, which is many millions of kilometers removed from the exciting radiation of the star's photosphere (or surface). This is completely at variance with all the early theories of β Lyrae, because in most of these the secondary absorption spectrum was identified with the secondary component of the double star. Once we abandon this idea, we are left with the spectrum of only one stellar set of absorption lines, and it must come from the principal component of the double star—the one that is eclipsed at principal minimum.

Before we continue we must consider one further spectroscopic phenomenon. Figure 5 shows a series of spectra of β Lyrae taken in different phases. At the top is one taken immediately after principal minimum, and at the bottom, one taken just before principal minimum. On these two plates the spectral absorption lines of the principal, or B9, component appear indistinct; for example, Mg II 4481A is diffuse and broad. So are the numerous lines of Fe II. Only the lines of helium and hydrogen remain strong and sharp, but they are not principally due to the B9 star. Rather, they originate in the secondary absorption spectrum, which we have just attributed to a nebulous mass of gas at a great distance from the star.

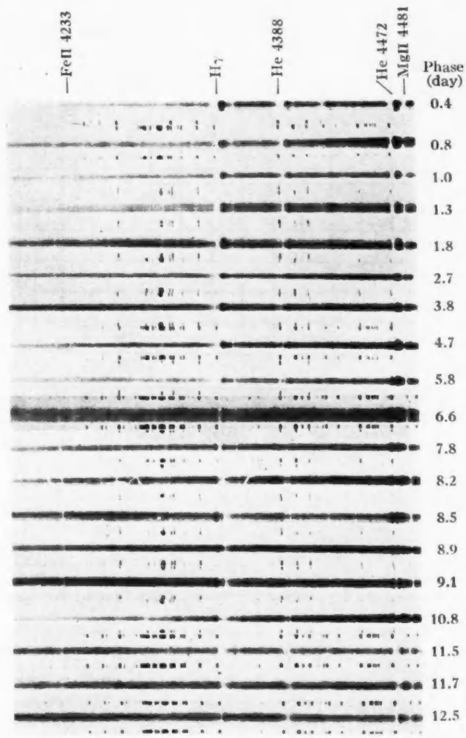

FIG. 5. Spectra of β Lyrae.

The broad and diffuse appearance of the B9 lines is not an unusual phenomenon among eclipsing variables at times just preceding and just following the center of an eclipse. Its origin is interesting. The star rotates around its axis so that one limb approaches us while the other recedes. Usually this causes only a symmetrical widening of all absorption lines. But when in double stars, one component begins to encroach upon the visible disk of the other, the latter's spectral lines are rendered unsymmetrical; the unobscured rim remains visible and extends the wing of the absorption line in one direction. If the eclipse is total, the line of the eclipsed star disappears completely, only to reappear a while later unsymmetrically displaced toward the other side. But if the eclipse is annular, so that a ring of the large eclipsed primary remains visible, the spectral lines are diffuse at the center of the eclipse, because, relatively speaking, the approaching and receding limbs contribute at this time more toward the formation of the spectral line than they do when there is no eclipse.

The unsymmetrical displacements of the lines and their broadening have both been observed in β Lyrae, first by R. A. Rossiter, of the University of Michigan. We conclude that an eclipse actually does take place, for if the light variation were solely caused by the elliptical shapes of the

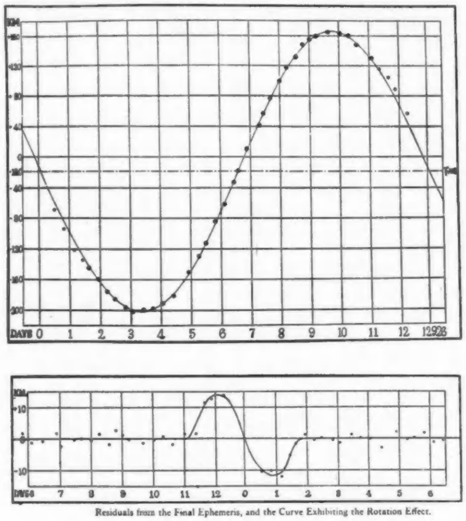

FIG. 6. Velocity curve of β Lyrae showing effect of unsymmetrical rotational broadening of lines during partial phase of principal eclipse [according to Rossiter].

two stars there would be no unsymmetrical shifting of the lines. The rotational effect is shown in the velocity curve in Fig. 6. For our purpose it is important to notice that the unsymmetrical broadening of the lines begins two days before center of eclipse and ends two days after it. This can mean only one thing: the entire principal eclipse lasts four days.

We must next return to a consideration of the light curve. Figure 7 shows one determined by Stebbins and Huffer, of the University of Wisconsin. In Fig. 8 the same curve is shown again, but in addition vertical lines have been drawn to mark the four days of the principal eclipse. Now consider what happens at secondary eclipse. The velocity curve is almost exactly a sine curve. Hence, it represents simple harmonic motion. The orbit is a circle, and the relative positions of the two stars are exactly reversed from what they were at principal minimum. The duration of the secondary minimum must also be four days.

Of the entire period of 13 days, 8 are spent in the eclipses. This leaves 5 days, or 2.5 on each side, which are free of eclipse. During these intervals the light should be constant, provided the stars are spherical in shape. The fact that the light is not constant proves that the stars are not spherical, and we must correct the light curve for the tidal elongation of the two bodies.

The corrected, or *rectified*, light curve is obtained in the following way. We know that, between the end of the principal and the beginning of the secondary eclipse, the rectified light curve must be constant. We also know that 2 days after principal minimum we are no longer seeing the star as a small circular disk but as an ellipse—the projection upon the background of the true tidal ellipsoid, turned about halfway. Hence the observed light at this phase is already more intense than it would be if the stars were true spheres. We could, from geometrical considerations, compute the projected area; but for our purpose it is sufficient to state that the rectified curve at phase 2 days will lie below the observed curve by an amount that is very roughly one-half of the excess which occurs at phase 3.5 days, when the ellipsoids are seen with their largest projected areas. Hence we draw the rectified curve in such a way that the correction at phase 2 days is about half of what it is at phase 3.5 days. At both minimums the projected disks are circular and the rectified curve agrees with the observed curve.

Notice how important it is to rectify the curve before drawing from it any conclusions with regard to the eclipses: the principal eclipse was observed to have a depth of 0.9 stellar magnitude, whereas the rectified curve gives only 0.6 magnitude. The depth of the secondary eclipse was observed to be 0.4 magnitude; the rectified depth is 0.1 magnitude. The differences between these two sets of values are explained by Maupertuis' mechanism of rotating ellipsoidal stars. The ellipticity of the stars which produces the required change in brightness approximately corresponds to a value of 0.75 for the ratio of the smaller axis of the ellipsoid of rotation to the longer (directed toward the center of the other star).

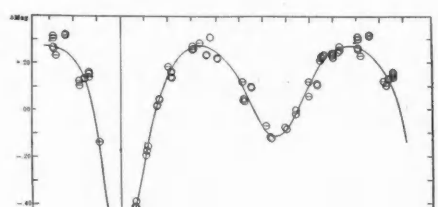

FIG. 7. Light curve for β Lyrae [Stebbins and Huffer].

Let us now assume that both stars are spherical, their radii being equal to the smaller axes of the two ellipsoids. The corresponding light curve is the one derived from the process of rectification. Although the abscissa of this light curve is expressed in the conventional astronomical unit of brightness—the stellar magnitude— it is more useful here to express the depths of the two minimums in terms of intensities I. By definition,

$$\Delta \text{ magnitude} = -2.5 \log I_1/I_2. \qquad (5)$$

Substituting the two values from the rectified light curve in the left-hand member, we obtain

$$-0.6 = 2.5 \log \frac{I \text{ (principal eclipse)}}{I \text{ (normal)}}, \qquad (6)$$

$$-0.1 = 2.5 \log \frac{I \text{ (secondary eclipse)}}{I \text{ (normal)}}; \qquad (7)$$

or

$$I \text{ (principal eclipse)} = 0.58\ I \text{ (normal)}, \qquad (8)$$

$$I \text{ (secondary eclipse)} = 0.91\ I \text{ (normal)}. \qquad (9)$$

The question now is: Can we determine the relative radii of the two stars? We shall neglect here such refinements as the reflection effect which produces an increased amount of light on the two sides of the components facing each other, and shall be satisfied with a crude analysis. A complete discussion of the photometric problem is not intrinsically difficult and has been performed many times; but here we are concerned merely with a simple illustration of the problem involved.

We know that the eclipse lasts 4 days. The entire period is 12.9 days. The ratio of 12.9/2

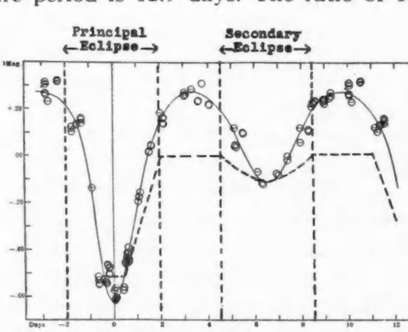

FIG. 8. The rectification of the light curve.

must be equal to the ratio of the entire path $2\pi r$ (where the meaning of r is, of course, different from that used in Eq. (3)) to the length of arc traveled by the secondary component around the primary from the moment the partial eclipse begins until the moment of center of eclipse (Fig. 9). This latter arc is approximately equal to

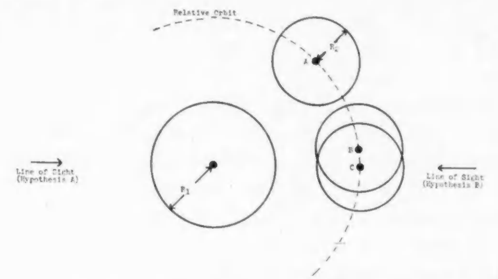

FIG. 9. Derivation of radii of eclipsing stars. At the beginning of the partial phase the center of the companion is in A; at the beginning of the total phase [hypothesis (A)] or annular phase [hypothesis (B)], in B; at the center of the eclipse, in C. The arc AC is nearly equal to R_1+R_2 and the arc BC, to R_1-R_2.

the sum of the radii of the two stars, R_1+R_2. The fact that this is not exact would be of importance in a real solution, but here we may adopt the approximation and write

$$2\pi r/(R_1+R_2) = 12.9/2. \qquad (10)$$

Adopting r as the unit of length, we solve for R_1+R_2 and find

$$R_1+R_2 = 0.97. \qquad (10')$$

The sum of the radii is almost exactly equal to the distance r between the centers of the stars. The stars are almost in contact. In reality we must still allow for the inclination of the orbit, which we have here tacitly assumed to be 90° but is probably more nearly 70°. This and other refinements give, more precisely, $R_1+R_2=0.75$.

If the eclipse were total we could also derive the absolute value of the difference R_1-R_2. During the phase of totality the light curve must give an essentially flat minimum. But the so-called effect of darkening at the limb, which we have disregarded in this simplified solution, would destroy the constancy at minimum. Perhaps we are entitled to conclude from the light curve that there is a nearly constant phase lasting half a day on each side of central phase.

We can then write

$$2\pi r/(R_1 - R_2) = 12.9/0.5, \tag{11}$$

or

$$R_1 - R_2 = 0.24. \tag{11'}$$

From geometrical considerations we easily see that this procedure is correct irrespective of whether the eclipse is total or annular. We now have two equations, Eqs. (10′) and (11′), which yield

$$R_1 = 0.60, \quad R_2 = 0.36. \tag{12}$$

But we are still uncertain as to which of the two stars—the one in front, or the one behind—is the larger at principal eclipse. We only know, from the spectrographic evidence, that the B9 component stands behind the other, invisible component at principal eclipse. The two possibilities are illustrated in Fig. 10.

Let us designate the surface brightness of the larger star by i_1 (per area of its projected surface) and that of the smaller component by i_2. Then $\pi R_1^2 i_1$ and $\pi R_2^2 i_2$ are the total luminosities* of the larger star and the smaller component, respectively. Outside of the eclipses we observe the combined light of both stars, $\pi R_1^2 i_1 + \pi R_2^2 i_2$. During the total eclipse, the light of the smaller component is completely shut off, and we observe $\pi R_1^2 i_1$. During the annular eclipse, a rim of the larger star remains visible, and the observed amount of light is $(\pi R_1^2 - \pi R_2^2) i_1 + \pi R_2^2 i_2$. We now compute the light lost at each eclipse:

Loss at annular eclipse $= \pi R_1^2 i_1 - \pi R_2^2 i_1 + \pi R_2^2 i_2 - \pi R_1^2 i_1 - \pi R_2^2 i_2 = -\pi R_2^2 i_1$;

Loss at total eclipse $= \pi R_1^2 i_1 - \pi R_1^2 i_1 - \pi R_2^2 i_2 = -\pi R_2^2 i_2$.

The ratio of these two losses is $-\pi R_2^2 i_1 / -\pi R_2^2 i_2 = i_1/i_2$. We can make two hypotheses: (*A*) that the shallower eclipse is annular, and (*B*) that the principal eclipse is annular. Accordingly, we obtain two solutions:

$$(A) \quad \frac{i_1}{i_2} = \frac{1-0.91}{1-0.58} = \frac{0.09}{0.42} = 0.2, \tag{13}$$

* The term *luminosity* is used here to designate the real brightness of a star, a quantity which is similar to the luminous flux but which usually applies to that range of wave-lengths in which observations have been made. If we are concerned with visual observations, the luminosity represents the visible radiations; if the observations are photographic, the luminosity represents that range of frequencies for which the photographic plate is sensitive.

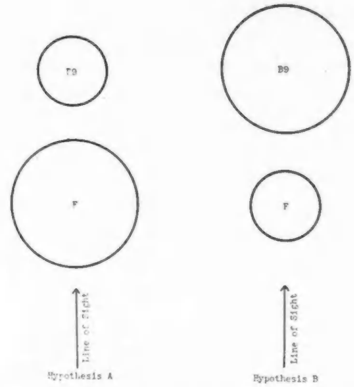

FIG. 10. Two possible solutions of the light curve for principal eclipse.

$$(B) \quad \frac{i_1}{i_2} = \frac{1-0.58}{1-0.91} = \frac{0.42}{0.09} = 4.7. \tag{14}$$

These results are important because they tell us how much more energy one component radiates, per unit area of its surface than the other.

In hypothesis (*A*) we assumed that the secondary eclipse is annular; hence the principal eclipse must be total. The B9 star is behind and is the smaller of the two; its surface brightness is i_2. The surface brightness of the large star in front is five times smaller.

In hypothesis (*B*) we assume that the principal eclipse is annular. The B9 star is still behind, and is therefore the larger. Hence in this case its surface brightness is i_1 and is, from Eq. (14), about five times larger than that of the smaller eclipsing star. The geometrical relations corresponding to our two hypotheses are illustrated in Fig. 10. In both cases the star which is in front at principal eclipse must have a less brilliant surface. But in one case, (*A*), it is the larger component, whereas in the other case, (*B*), it is the smaller.

It is important to realize that, so far as the light curve alone is concerned, both solutions are equally good; we have as yet no reason for preferring one hypothesis to the other. However, our analysis can be pushed further if we remember that the temperature of the principal component of β Lyrae, the B9 star, is, in accordance with its spectrum, about 15,000°K. With the help of the Planck radiation law,

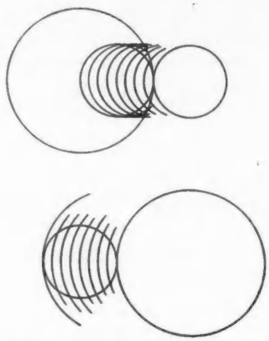

FIG. 11. Equivalence of hypotheses (A) and (B).

$J_\lambda = C_1\lambda^{-5}(e^{c_2/\lambda T}-1)^{-1}d\lambda$, we infer that, in the wave-length region 5500A, the B9 star radiates 1.57×10^{16} erg cm^{-2} sec^{-1} $\Delta\lambda^{-1}$. At 8000°K, J_{5500} is only 2.95×10^{15} erg cm^{-2} sec$^{-1}\Delta\lambda^{-1}$. The ratio, $2.95\times10^{15}/1.57\times10^{16}=0.2$, is exactly that required by Eqs. (13) and (14). Hence we conclude that the temperature of the eclipsing star at principal minimum is 8000°K, and the corresponding spectral type is F.

Now, the observed spectrum shows no absorption features that are characteristic of spectral type F (similar to that of the star α Persei). We conclude that the total luminosity of the secondary component of the binary is too small; the exposure is too short to bring it out without burning out the photographic emulsion with the light of the B9 star.

In hypothesis (A), Fig. 10, the hot star is the smaller of the two. Its total luminosity is proportional to

$$\pi R_2^2\times1.57\times10^{16}\text{ erg sec}^{-1}\ \Delta\lambda^{-1},$$

whereas that of the large secondary is proportional to

$$\pi R_1^2\times2.95\times10^{15}\text{ erg sec}^{-1}\ \Delta\lambda^{-1}.$$

The ratio of the total luminosities is

$$\frac{\text{principal star}}{\text{secondary star}}=\frac{R_2^2\times1.57\times10^{16}}{R_1^2\times2.95\times10^{15}}=1.7.$$

Hypothesis (B) predicts the ratio:

$$\frac{\text{principal star}}{\text{secondary star}}=\frac{R_1^2\times1.57\times10^{16}}{R_2^2\times2.95\times10^{15}}=13.$$

Hypothesis (A) predicts that the two stars are of comparable apparent brightness (the principal star is less than twice as luminous as the secondary), while hypothesis (B) predicts that the B9 star is 13 times more luminous than the secondary component. A more exact computation, based upon a solution of the light curve according to the standard procedure of H. N. Russell, makes this difference in the two ratios even more startling. For example, S. Gaposchkin finds for hypothesis (B) a ratio of 24 in favor of the B9 star, and many years ago Shapley found for hypothesis (A) a ratio of 1.5.

The entire problem of β Lyrae hinges upon the adoption of the correct hypothesis. If we choose the wrong one we shall find innumerable difficulties—most of them small individually but overwhelming in mass. It is a matter of record that nearly all of the older investigators adopted hypothesis (A). We have already seen that the light curve as such gives no preference to either hypothesis. Figure 11 shows that the two hypotheses are photometrically equivalent. The areas eclipsed after equal intervals are identical in a circular orbit, with spherical stars, whether the large star is in front or behind. Hence, from the durations of the eclipses, we cannot distinguish between the hypotheses. Our discussion of the surface brightnesses has, moreover, shown that by adjusting them we can satisfy the depths of the two eclipses under each of the two hypotheses.

Why, then, did these early investigators prefer to make the B9 star small? I believe there were two rather weighty reasons. In the first place, there is always a certain temptation to think of the deep eclipse as being total, and of the shallow eclipse as being annular. In the majority of eclipsing binaries this assumption has given satisfactory results, and by analogy it was supposed to apply to β Lyrae. But even more important is the following consideration, which was clearly stated in Shapley's classic monograph on eclipsing variables (1913). The spectrographic investigations had revealed the existence of two distinct sets of absorption lines; and R. H. Curtiss, of the University of Michigan, had concluded in 1911 that β Lyrae showed two continuous spectra, the brighter one being that of the B9 star, the fainter one, connected with

the secondary set of absorption lines, being attributed to the second binary component. This system of unequal, but spectroscopically observable, components was preferred by Curtiss and was adopted by Shapley. If the light of the secondary component was to be at all visible, even during principal eclipse, it was essential that the total luminosities should not be too different, and hypothesis (A) offered the only acceptable solution. In hypothesis (B) the brilliant rim of the blue, B9, star would far outshine the dimmer, secondary component, even at principal minimum.

As soon as we adopt hypothesis (A), our troubles begin:

1. The secondary spectrum corresponds to type B2, or to a temperature of 25,000°K, not to spectrum F, or temperature of 8000°K, as is required by the surface brightnesses.

2. The observed secondary spectrum is not that of a real star, but of a dilute mass of gas, at a distance of millions of kilometers from any stellar photosphere.

3. The measurements of radial velocities of the secondary absorption lines reveal no periodic change of opposite phase to that of the B9 star. This can be reconciled with the demands of orbital theory only if the secondary has an unreasonably large mass—15 or 20 times that of the primary. Such a mass ratio would be inconsistent with the fact that the secondary is less luminous than the primary.

4. The measured motions of the secondary lines do not, on the average, agree with the speed of the entire system of β Lyrae through interstellar space, this being a speed of approach of 19 km sec^{-1}. Instead, they show large speeds of approach, in all phases, ranging for different lines from about 50 to more than 100 km sec^{-1}. Such large speeds suggest expansion of a gaseous nebula surrounding the system of β Lyrae rather than orbital motion.

5. Accurate measurements of the color of β Lyrae with photoelectric photometers by Elvey and others show conclusively that β Lyrae is redder at principal minimum than elsewhere in the light curve. In the words of the French astronomer Danjon, "everything takes place very much as though that component which is eclipsed at principal minimum is the bluer of the two." This is in accordance with the photometric solution and once more violates the proposed identification of the secondary component with the B5 absorption spectrum.

6. At principal minimum the lines are broad, but even in the middle of the eclipse there is a strong B9 spectrum in sight. If the principal eclipse were total, these lines could belong only to the secondary, and the inevitable conclusion would be that its spectrum is neither F, nor B5, but B9—being an exact duplicate of the spectrum of the principal component. This conclusion would violate both the photometric and the spectrographic evidence. Perhaps, the eclipse is partial, and the inclination far from 90°. But then the absorption lines from the polar cap of the principal star which would remain visible at the center of the eclipse should appear narrower than normal, because the extreme equatorial limbs of the B9 star would be eclipsed and the rotational broadening of the lines would be small.

The evidence is overwhelmingly against hypothesis (A). If we try hypothesis (B) we must first agree to disregard the B5 absorption lines. But we have already decided to do so. In fact, R. H. Curtiss long ago proposed as a possible, though then considered unlikely, solution the idea that these lines originate in a nebula. The dilution effect now makes this assumption virtually a certainty, and we are free to adopt hypothesis (B). The secondary is invisible because it is too faint to show with the exposures required for the principal star. All six difficulties are removed, and, in principle, the problem of β Lyrae is solved.

But there remain many interesting details to be cleared up. First, let us look into the question of the actual dimensions of the system of β Lyrae. We infer from the velocity curve in Fig. 6 that the greatest speed of recession is 160 km sec^{-1}, while the greatest speed of approach is 200 km sec^{-1}. The speed in the orbit is, accordingly,

$$V_{\text{orb}} = \tfrac{1}{2}(160+200) = 180 \text{ km sec}^{-1}.$$

We must remember that this represents the motion of the B9 component in its circular orbit around the center of mass of the system. The length of this orbit is

$$2\pi r^1 = 180 \text{ km sec}^{-1} \times 12.^d 9 \times 24^h \times 3600^s = 2\times 10^8 \text{ km}.$$

Hence the radius r^1 of the orbit is 3×10^7 km. But this is not the radius of the relative orbit of the secondary component around the primary, which we designated as r in Eq. (10). To determine the latter, we must know the mass ratio $m_{\text{B9}}/m_{\text{F}}$, because

$$r^1/(r-r^1) = m_{\text{F}}/m_{\text{B9}}. \tag{15}$$

Although the mass ratio cannot be determined observationally, because we observe only the lines of one star, various indirect considerations suggest that this ratio is between 0.5 and 1.0. If we adopt 0.5, Eq. (15) yields $r = 3r^1 = 10^8$ km, and, from Eq. (12),

$$R_{\text{B9}} = 0.6\times 10^8 \text{ km}, \quad R_{\text{F}} = 0.36\times 10^8 \text{ km}.$$

The mean radius of the sun is 7×10^5 km. The B9-component is almost 100 times as large, and the F-component 50 times as large, as the sun. The principal component is a supergiant, although its diameter is not exceptional. The F-component is somewhere between an ordinary giant and a supergiant. There is no confirmation from the spectrum of the latter, since it is unobservable. But the former shows little Stark effect and, hence, has a low atmospheric pressure, such as we would expect in a supergiant.

An estimate of the masses of the two stars is obtained from the relative speed in a circular orbit,

$$V^2_{\mathrm{circ}}=k^2(m_1+m_2)/r.$$

For the earth V_{circ} is 30 km/sec, r is 1.5×10^8 km and m_1+m_2 is 1. For β Lyrae $V_{\mathrm{circ}}=V_{\mathrm{B9}}+V_{\mathrm{F}}=180+360=540$ km/sec and r is 10^8 km. Substituting these values and solving for $m_{\mathrm{B9}}+m_{\mathrm{F}}$, we find

$$m_{\mathrm{B9}}+m_{\mathrm{F}}=220 \text{ solar masses,}$$
$$m_{\mathrm{B9}}=146 \text{ solar masses,}$$
$$m_{\mathrm{F}}=\ \ 73 \text{ solar masses.}$$

These masses are large but they are not exceptional. They depend upon the assumed mass ratio. It is easy to see that, if the mass of the F star were less than 0.5 of that of the B9 star, the total mass would be still larger.

The luminosity of the B9 star may be inferred from its spectrum or from its mass. A recent estimate by G. P. Kuiper gives a visual absolute magnitude of -5. In other words, if β Lyrae were at a distance of 30 light years it would have an apparent magnitude of -5. (This is somewhat brighter than Venus.) In reality, the visual apparent magnitude at maximum is 3.5. Since the F-component contributes very little to the total light, we infer that the distance of β Lyrae is so great that it appears to be 8.5 magnitudes fainter than it would at 30 light years. From the relation

$$\textit{Absolute magnitude}=\textit{Apparent magnitude}+5-5\log(D/3),$$

we compute the distance D to be 1500 light years.

We have seen that the radius of the B9-component is 0.6×10^8 km. Hence the circumference of the equator, assuming that the star is spherical, is $2\pi R_{\mathrm{B9}}=3.8\times10^8$ km. It is reasonable to suppose that in a very close binary the period of axial rotation coincides with the period of orbital revolution. Hence the speed of rotation at the equator is

$$V_{\mathrm{rot}}=3.8\times10^8 \text{ km}/12.^{d}9\times24^{h}\times3600^{s}$$
$$=350 \text{ km sec}^{-1}.$$

This value is unexpectedly large. The B9 absorption lines are appreciably broadened; but, by comparing the observed line contours with those of a nonrotating star, Wares found an equatorial speed of rotation of only 40 km sec^{-1}. This refers to the time of secondary minimum, when the cross section of the B9 star is smallest. But even at maximum the lines are not very broad, and the speed of rotation can hardly exceed 75 km sec^{-1}. Perhaps we have overestimated the mass ratio. Kuiper prefers a different value. Moreover, the crude manner in which we have solved the light curve leads to excessive radii. Gaposchkin, for example, does not allow the two stars to touch. Nevertheless, it appears from recent computations by Kopal, that the discrepancy is real: the value determined by Wares from the spectrograms is smaller than the theoretical value by a factor of at least three. Kopal has privately suggested that darkening at the limb may account for the small observed result. Yet the discrepancy has not been fully explained, and thus the problem is not completely finished. Nevertheless, the evidence in favor of the proposed model is so strong that the difficulty with the rotation must, for the time being, be ignored.

If we accept this model we are faced with a rather unusual system: two stars of different mass and size are almost in contact. Kuiper has recently shown that the outer layers of the components are actually in contact. From dynamical considerations he concludes that in such a system matter will stream from the large to the smaller component, and, under certain conditions, may flow out into space from that point on the secondary which is most distant from the principal component. It is of interest to investigate in detail the spectrum during the principal eclipse in order to ascertain whether Kuiper's predicted streams actually exist.

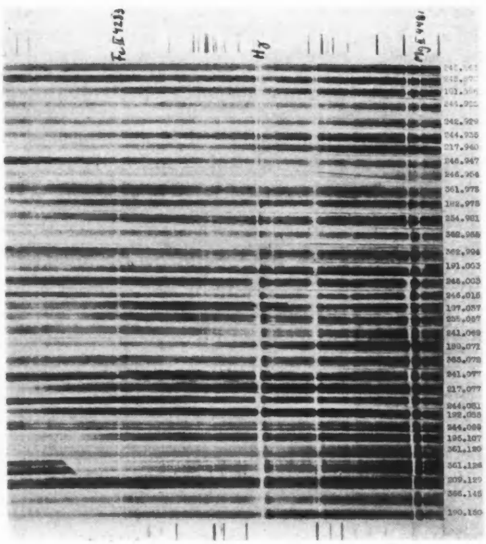

FIG. 12. Spectra of β Lyrae near principal minimum, showing satellite absorption lines.

This has been done with the help of spectrograms secured at the Yerkes Observatory. The most remarkable phenomenon is the appearance about one day before the middle of the principal eclipse of a set of absorption lines of H, He, I, Mg II, Si II, Fe II, and so forth, with a displacement of $+180$ km sec^{-1}. These new "satellite" lines (Fig. 12) rapidly increase in strength, then equally rapidly become fainter and finally disappear completely a quarter of a day prior to middle of eclipse. An even stronger set of absorption satellites appears a few hours after the middle of eclipse and lasts approximately one day. This set of lines contains strong H and He I, only traces of Mg II, Si II, and no measurable amount of Fe II. Their displacement is about -250 km sec^{-1}.

The interpretation of these violet satellites after middle of eclipse and of the red satellites immediately preceding middle of eclipse was difficult in terms of the old theory of β Lyrae. On our present theory the violet satellites represent a stream of hot gas flowing from the B9 star around the following side of the F star. Kuiper has computed the orbits of the stream particles and has shown that they will actually describe paths along the following side of the F-component. Part of the gas, presumably that which consists of the slower moving atoms, will rather closely hug the surface of the F star; thus it will be cooled while in contact with the cooler surface of this component and hidden by the F star from the radiation of the B9 star. This gas finally returns to the B9 star, thereby producing the red satellites.

The presence of Mg II 4481 in the satellite spectra is important. It proves that the dilution of the radiation, though still appreciable, is much less than for the nebulous B5 layer. We, therefore, locate the streams inside of this layer. The sudden disappearance of the red satellites and the equally sudden appearance of the violet satellites after minimum light are due to obscuration caused by the apparent disk of the F-component. The times of appearance of the red satellites and of disappearance of the violet satellites are physically not important. A large part of the disk of the B9 star must be eclipsed before the absorption in the two columns of gas, whose cross sections are much smaller than that of the B9 star, can be observed.

A part of the gas which flows from the B9 star toward the F star is lost through a narrow outlet at the critical point of the latter. A marked strengthening of the B5 absorption lines about one day after principal minimum is observed. This very pronounced asymmetry with respect to principal minimum had been noticed by Miss Maury, but its importance was not realized until Kuiper showed theoretically that the gas which is lost at the outlet of F is deflected because its angular momentum is conserved; the revolution of the system causes the gas to lag behind the F-component. This lag accounts for the unsymmetrical strengthening of the B5 lines one day after principal minimum.

The total absorbed energies of the B5 lines are a measure of the numbers of atoms in a column of unit cross-sectional area within the nebulous layer. The B5 lines are broad and resemble lines widened by turbulent motions. For all such lines, except only the very strongest, the total absorbed energy is proportional to the number of atoms in the lower level of the corresponding transition.

After the maximum of intensity has been reached, the B5 lines rapidly decline in strength.

They are very weak three and four days after principal minimum. Five and six days after principal maximum they are blended with the B9 lines, but thereafter they increase rapidly in intensity (Fig. 13).

This cycle in the intensities of the B5 lines is not easily explained. Kuiper remarks that during their ejection from the F star the atoms are hidden from the light of the B9 star and the ionization must be low. Incidentally, it is the B9 star to which we must attribute the ionizing and exciting action.

Kuiper finds from his dynamical analysis that the atoms spiral outward, giving the impression observationally that the B5 layer is expanding. Possibly, several windings of Kuiper's spirals are contained in the observed B5 layer. But the effective thickness of the latter cannot be great, because we fail to observe in its spectrum the characteristic features of stratification.

One further comment is required to understand the nature of the B5 layer. Can we distinguish, observationally, between a complete shell which surrounds the B9 star from all sides, and a ringlike structure which is limited to the equatorial plane? The answer is: Yes. The nebulous ring produces very strong absorption lines one day after principal eclipse. These lines are similar to those of a B5 supergiant in intensity. Except for dilution effects we are not aware of any appreciable differences in the composition of the nebula and a normal reversing layer. The helium lines may be abnormally strong, but hydrogen is certainly abundant. Now, a gas which produces line absorption must produce also general absorption over all wave-lengths. The general opacity in a stellar reversing layer of high temperature is caused largely by photoelectric ionizations at the heads of the various series. In the ordinary photographic and visual regions of the spectrum continuous absorption at the Paschen limit is important. There are other effects, such as free-free transitions of electrons, nonselective electron scattering, and continuous absorption processes in helium. As long as the composition, temperature and pressure of the nebulous layer are unknown, we cannot accurately compute the amount of the

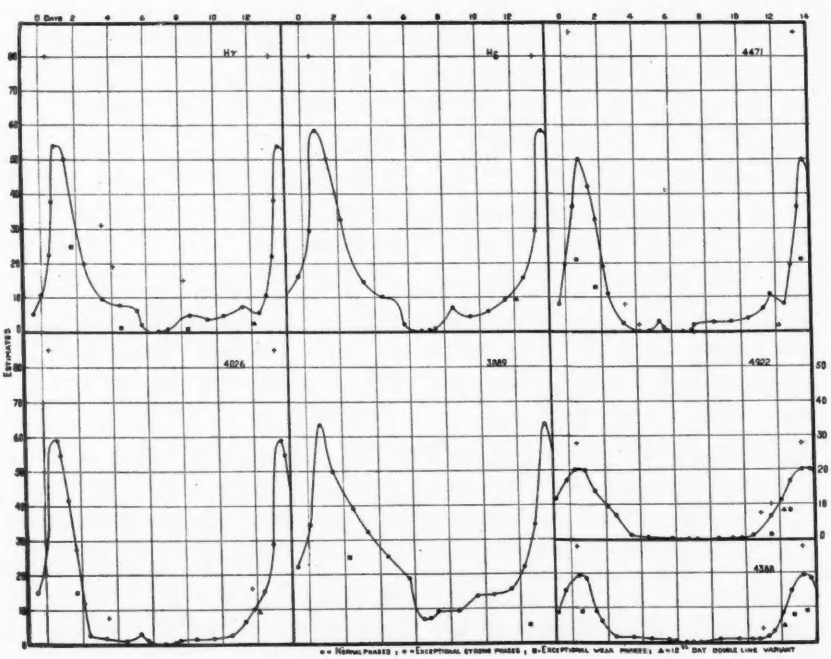

FIG. 13. Intensities of B5 lines as function of phase counted from principal minimum [Miss Maury].

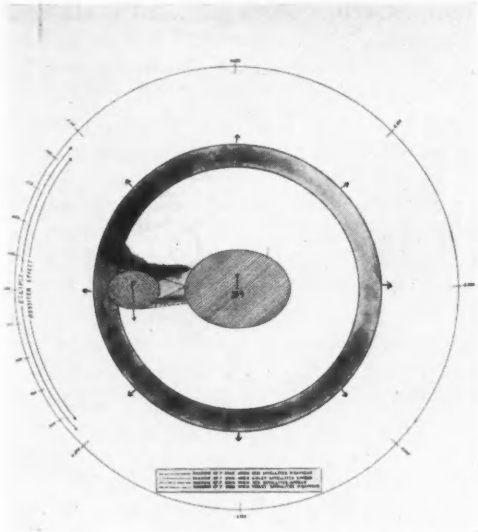

FIG. 14. Schematic representation of observational data.

continuous absorption. But, by analogy with stellar reversing layers, it is reasonable to suggest that the optical depth κs for continuous absorption (the product of the absorption coefficient κ and of the thickness s of the layer) in the nebulous shell must be of the same order of magnitude as the optical depth of a stellar reversing layer, because the total absorptions of the lines are similar. For a stellar reversing layer the optical depth is of the order of 0.5. This means that if we could remove a representative sample of the reversing layer and place it in front of a luminous source, the intensity of the latter would be reduced to a fraction $e^{-0.5}$ of the original intensity. The optical depth of the nebulous mass must be of the order of 0.3. A mass of gas having this appreciable amount of continuous absorption must, in view of Kirchhoff's law, emit continuous radiation; and the flux of the latter can be computed if the surface area of the nebula is known. It will overlie the spectrum of the B9 star and will tend to fill up the absorption lines of the latter.

Theoretically we foresee three distinct effects attributable to the continuous opacity of the nebula: (1) its continuous absorption will weaken the transmitted light of the B9 star inside; (2) its continuous emission will fill in the absorption lines of other objects, irrespective of whether the latter are behind the nebula or in front of it; (3) its continuous absorption will alter the process of line production in the reversing layer of the star inside.

A consideration of the second process leads to the conclusion that the total surface of the nebula cannot be very much larger than that of the B9 star. On the other hand, the depth of the B5 lines one day after minimum shows that at this phase the area of the nebula which is seen projected upon the disk of the B9 star cannot be much smaller than the latter. This strongly suggests that the nebula has the shape of a ring, of a cross section not much smaller than the B9 star. The third process is of great interest: in several other stars nebulous shells appreciably cut down the intensities of the absorption lines that come from the reversing layer. This is attributed to the combination of all three processes in the case where the shell is a sphere and surrounds the star from all sides. The remarkable thing in β Lyrae is that the absorption lines of the B9 star are not greatly weakened in comparison with such an object as β Orionis. Moreover, throughout the period the true B9 lines are roughly constant in intensity. This can well be reconciled with the hypothesis of a ring whose projected area is small at phase 1 day, but is large at phases 4, 5 and 6 days after principal minimum. It cannot be reconciled with the hypothesis of a spherical shell whose hemisphere centered around phase 1 day has an optical depth of 0.3 while its opposite hemisphere has an optical depth of nearly zero.

Figure 14 shows a schematic representation of the observations. We are not able to discern structure within the B5 ring. However, Kuiper's analysis shows that the orbits of the particles are spirals, which gradually wind around the system in ever increasing arms (Fig. 15). This pinwheel structure gives rise to the emission lines as well as to the B5 absorption lines. But while the latter are produced by those regions of the spiral which at any given moment happen to lie exactly in front of the bright B9 supergiant, the emission is produced by the entire uneclipsed mass of the nebula. Except for the effect of obscuration by the two stellar bodies, we should expect that the intensities of the bright lines

would remain substantially constant throughout the 13-day period. Instead, as we had seen in the beginning, the early spectroscopists had detected marked variations in the emission lines, and these variations have been fully substantiated by all later observers. At first sight the discrepancy looks serious; but we soon realize that the constancy of the emission lines would hold only if all our exposures were made of the same duration, throughout the 13-day cycle. Now, that is obviously not the case. When the star is at maximum light the exposures are short; when it is at principal minimum we must expose almost three times longer in order to bring out the continuous spectrum with its absorption lines. The emission lines are then overexposed and should appear stronger on the photographic plates. This is exactly what the observations have shown: Mrs. McLaughlin, at the University of Michigan, has proved that when the intensities of the emission lines are corrected for the changes in the brightness of the star they show little, if any, variation.

An important question, not yet fully investigated, is whether the emission lines show changes in radial velocity. Many years ago Belopolsky in Russia derived an orbit from radial velocity measures of the bright lines. The orbit was found to be circular, and the phases were exactly 180° later than those of the B9 star, but the range of the velocity curve was very much smaller, of the order of 150 km sec^{-1}. The usual interpretation would be that the orbital velocity of the gases producing the bright lines is 75 km sec^{-1}. However, we are here dealing with a nebulous ring or spiral, the gases of which are distributed on both sides of the center of mass. Hence, it is more reasonable to suppose that the total number of gaseous atoms in the spiral structure is larger on that side in which the F star is located than on the opposite side. Considering the theoretical conclusion of Kuiper that the atoms tend to stream from the B9 star to the F star, and only in part are thrown into the spiral ring, it is not unreasonable to expect that the nebula will actually be brighter on that side where phase one day after principal minimum is located.

Another interesting result is the great width of the emission lines. We know from astronomical observations, as well as from physical theory, that in a nebula the line widths are almost wholly produced by the Doppler effect. Now, the Doppler motions corresponding to the widths of these lines β Lyrae are of the order of some 500 km sec^{-1} —far in excess of the ordinary thermal motions of the atoms. Nor can the motions be of a turbulent character: We have seen that the widths of the B5 absorption lines are much smaller than those of the emission lines; and, while they lead to appreciable turbulent velocities, these are of an

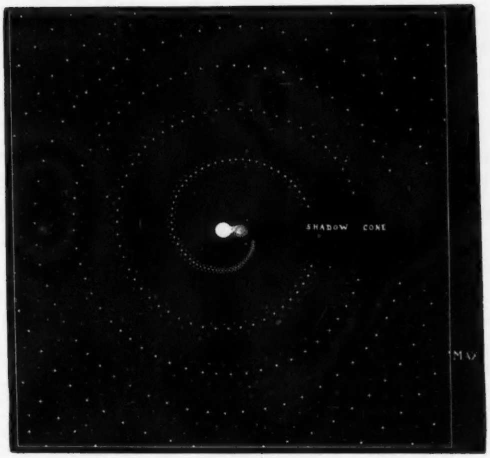

FIG. 15. Kuiper's theoretical representation of β Lyrae.

entirely different order of magnitude, perhaps about 50 km sec^{-1}. The only reasonable explanation of the widths of the emission lines is in terms of orbital motion in the gravitational field of the two stars. Kuiper's computations give essentially the required velocities along the spiral arms, in a stationary frame of reference.

We must not confuse these motions with the observed velocities of expansion derived from the B5 absorption lines. The latter measure only the component in the line of sight of that small portion of each spiral arm which is projected upon the B9 disk, and whose motion along the spiral is almost entirely at right angles to the line of sight. It can, therefore, not be detected from the displacements of the absorption lines.

We are now able to summarize our results. The star is actually a binary, just as the older theory had predicted. However, the cool and relatively small star which turns around the hot supergiant is so much fainter in light that we cannot even photograph it; in the time required to record it, the image of the hot supergiant would be so completely overexposed that the photographic emulsion would be burned out. Of course, the distance of β Lyrae is so great that we cannot actually see the pinwheel structure of the expanding gases, or the motion of the faint companion around the primary star. Even the greatest telescope now in existence is much too small to bring this marvel to our eyes. We must be content with information secured by theory and indirect observation.

Imagine then a giant sun, so hot that its color is essentially blue, so large that a good

portion of the entire solar system could be hidden within its confines, and so brilliant that our sun would completely disappear in its glare. At a short distance, probably less than the radius of the large star, is another sun, yellow in color, and relatively cool, though hotter and considerably larger than our sun. This yellow star revolves around the blue supergiant once in 13 days. Its gravitational attraction upon the supergiant is tremendous. Tides tend to elongate the latter, until its shape is like that of an egg, and until some of its outer gases coalesce with the gases of the yellow sun. As soon as contact between the two stars is established, matter will start rushing from the hot supergiant toward the yellow star, and the speed of this eruption is at least 100 mi sec^{-1}. Some of this erupted matter sweeps along the surface of the yellow star, where it is cooled and reduced in speed, until it finally returns to the parent star with a speed of some 50 mi sec^{-1}. But only a small part—probably less than half—of the erupted matter ever returns to the blue supergiant. Under the attractive force of the two stars and in a way predicted by some of the basic laws of motion, a part of the erupted gas is thrown past the yellow star, and spirals out at first in a narrow band, later in an ever widening spiral arm, until it is gradually lost in the space between the stars. This spiral is hot—almost as hot as the blue supergiant; and the gases shine in all the colors characteristic of electric discharges in gases—luminous hydrogen with its red tinge, helium with yellow and green, neon with its red; the matter spirals out with a speed close to 100 mi sec^{-1}. The size of this gigantic pinwheel may be 10^8 mi, and its distance from us is about 1500 light years. The mass of the principal star in the system is about 100 times larger than that of our sun, and its output of light is about 10,000 times larger.

No other stars known to astronomers show a similar pinwheel structure, and this includes the thousands of faint stars which have been studied with large telescopes. But we should not forget that there are billions of other, still fainter, stars that have not as yet been investigated. It is likely that the pinwheel structure is not a frequent occurrence in the universe. We see that it must be an unstable structure, one which rapidly disintegrates and must relatively soon end. Whether the star loses all of its mass in the process, or whether the process stops long before an appreciable fraction of the gases is lost, is not known. Kuiper's theoretical analysis shows that all close double stars must undergo a process of the form described, until enough mass is lost to provide for complete clearance of the surfaces of the two stars at all times during their courses around each other. Single stars, such as our sun, probably never undergo the pinwheel stage.

The tidal elongation of the blue supergiant star in β Lyrae renders it appreciably unsymmetrical. In fact, the longest dimension of the star is almost 50 percent greater than the smallest. It so happens that the period of rotation of this star on its axis is exactly the same as the period of revolution of the yellow star around it, namely, 13 days. Hence, the blue star always shows the same side toward the yellow star. But from our earth we see the elliptical mass of the blue star gradually expose first its long side, then its short, circular cross section, so that the light varies in a continuous manner, exactly as Maupertuis suggested several hundred years ago.

Superposed on this gradual variation in light is the effect of the mutual eclipses of the two suns. The earth happens by chance to lie almost exactly in the plane of the pinwheel. Sometimes the small yellow star is in front of the blue supergiant. We then have an annular or ring eclipse of the latter, with a brilliant blue rim remaining visible around the relatively dim yellow disk of the secondary component. Then, a little more than three days later, both stars are visible side by side, and we obtain the full benefit of their combined light. After another interval of three days, or six and one-half days after the beginning, the blue star is in front, and the yellow star is completely eclipsed by the larger disk of the secondary. Nine and three-quarter days after the beginning both stars are visible, with their relative positions reversed; and 13 days later a new cycle begins.

The Opportunity of the Physics Teacher*

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IT will generally be agreed that physics is the most fundamental of the sciences, that some knowledge of it underlies them all and is therefore their indispensable prerequisite. For this reason alone the job of the teacher of physics takes on unusual significance. But from my point of view it is much more vital in the present stage of development of the United States than most physics teachers themselves realize. The main purpose of this paper is to point out why.

At no time or place in world history has any country, save the United States, attempted to extend to every youth within its borders the benefits of a general education up to the age of from sixteen to eighteen. But within the past forty years forty-two of our states have passed laws requiring school attendance of every boy and girl up to about that age. Some of our European critics call it a fantastic and ridiculous attempt, since so large a fraction of the population, 90 percent at least, it is said, must in any case gain its livelihood in manual or service pursuits of one kind or another.

There are two answers to this criticism. The first is that since all those engaged in the foregoing occupations are in any case voters, it is essential for the preservation of our free, democratic, American way of life that the attempt be made to give all voters sufficient education to enable them to vote intelligently.

The second answer goes farther and asserts that if our democratic way of life is to show itself really superior to other ways, such as the totalitarian way, it must succeed better than any other way both in bringing into leadership in the development of American civilization the ablest and most competent men the country produces and also in fitting each citizen into the niche in society which he is best fitted to occupy and in which he will be most effective for the purposes of society and therefore most happy for the purposes of his own life.

That last "and therefore" attacks, at its base, the fundamental fallacy that happiness in life has any relation to the magnitude of the responsibilities that one carries or the power that one wields. The gratification of mere physical or biological wants aside, the greatest satisfactions in life come from a sense of mastery of one's job and the greatest misery from a sense of incompetence, inability to succeed in doing well what one is expected to do. The average man is not happy in intellectual pursuits because he does not succeed well enough in them. They are too hard; they give him too many headaches. Educational philosophers and psychologists have repeatedly pointed out that the greatest satisfaction in life for all of us, including even the intellectually competent, comes from the mastery of manual skills such as underlie all sports and a large part of all artistry, in learning by endless repetition to do even service jobs with perfection and dispatch. Vastly more people are interested in *art* than in *knowledge.*

If the truth of these assertions is admitted, then the most important job of any universal educational system consists not so much in imparting knowledge, though that, of course, has its place, as in using the educational machinery from the age of thirteen on *for the purposes of selection*, or better, of *vocational guidance*, so as to discover just what *are* the aptitudes, interests and capabilities of each prospective citizen and so as to fit him into the niche in our society in which he can be most useful and therefore most happy. This will consist very much more often in steering him away from analytical, intellectual pursuits to which he is not adapted than in steering him into them.

Physics is admittedly the best subject in the whole curriculum for testing the analytical aptitudes and capacities of the student, that is, in finding out whether he is likely to make a success of any of the analytical pursuits such as are all the sciences, law, medicine, engineering, finance, management, government, and so forth. Probably the most kindly, the most humane, act that can be done to nine-tenths of the youth of

* Reply to the presentation of the Oersted Medal, December 30, 1940.

the land is to steer them away from, not toward, these difficult, analytical, intellectual pursuits. Obviously the way to accomplish best this objective of distributing the population most wisely and effectively among the available pursuits is to give as nearly as possible equal *opportunity* to every youth up to the age of from sixteen to eighteen to show to competent judges what is in him, what kind of capacities and interests and character he has, and to let the kind of vocation which he goes into for earning a living be the kind in which, in this probationary period, he has shown himself best adapted to succeed and be most content.

Let us look first at what kind of qualities in teaching are required to meet the requirements of this second objective of a universal educational system. The answer is quite clear. The most important job of the teacher is to know his students, every one of them, so that he will make as few mistakes as possible in rating their qualities and their capacities justly and accurately in order that he may steer them wisely. Talking entertainingly to a hundred or two hundred students is a wholly subordinate and trivial requirement of a good teacher. The great, indispensable requisite is conscientiousness in watching carefully and discriminatingly the way his students solve problems, the way they do their laboratory work, the way they answer examination questions, the way they pose questions of their own. This job cannot be delegated to anyone else without abdicating the main job of the teacher.

Such abdication may sometimes be necessary when the exigencies of the whole educational machinery require a teacher to change his job and become an administrator instead of a teacher, but even so it is of the utmost importance for the administrator, in performing his new function *of selecting good teachers*, to know what the prime requirement of a good teacher is, namely, conscientiousness in doing the job of selection and vocational guidance as well as it can be done. No professional guidance person can do that. It is the teacher's own job.

May I now digress one moment to say a word about what kind of steering is to be done for those who are not fitted to go on into the intellectual pursuits? That leads me to comment upon what, in the past, has been the most obvious and lamentable weakness of our whole American educational system, namely, the lack of an apprenticeship system operated in connection with industry into which, at the end of the high school course—the twelfth grade—the student whose place is obviously in the manual callings or in commerce can become expert in these vocations. The British Empire and the whole of Europe have done this job vastly better than have we in the United States. That is why, in the past, most of our skilled mechanics, and even skilled service people, such as waiters in hotels, have had to be imported from abroad. Fortunately this lack has recently been recognized by some of our educational agencies, and they are now beginning to take steps to meet this enormous need.

Let me now go back to the first reason given above for the attempt to keep every youth in the country in the secondary educational system up to the age of from sixteen to eighteen. This attempt has so far succeeded in the United States that, according to official reports of the Department of Education, 66 percent of all the youth of secondary school age is now in school, and in some of the northern states the percentage is as high as 80.

This situation provides an opportunity such as never existed at any other place or time in history, for the future of any democratic country is assured if it can train 51 percent of its voting population to vote intelligently. With 66 percent of our youth in the secondary school, the school teacher, if he realizes his opportunity, can himself assure the preservation of our democracy, for example, by so educating that 66 percent as to eliminate the greatest internal menace to the future of the United States, namely, our political corruption, euphemistically called the American patronage system, a system which makes Congress the tool of political pressures, whether exercised by bonus racketeers or by unscrupulous elected officials. This system will destroy us if we do not destroy it, as England has destroyed it within the past hundred years, replacing what was as rotten a system as ours by an amazingly clean, nonpolitical public service—the most important pillar of democracy. Only intelligent voters can do this. Through our public schools

the feat can be accomplished in one generation. In other words, the future of our country is literally in the hands of the American school teacher.

But how does one learn to vote intelligently? The answer is, by beginning to get into his consciousness some idea of what is the *rational approach* to life instead of the irrational, superstitious approach, which was all that primitive man could use and is still used by many who do not realize that they are still primitives.

But what, in turn, is the rational approach? It is the approach that is based on *knowledge* instead of on ignorance, or prejudice, or hunch, or emotion, or tradition. The most important idea that can get into the minds of the youth of the nation is that *there is a core of definite established knowledge* in all fields, even the field of government, that must be the starting point and basis of all correct action, all wise conduct. This core is much larger in some fields than in others, and in all fields it is surrounded by a zone of the controversial and this in turn by the "great unknown"; but the first job of education in the intellectual sense consists in getting the student interested in finding out what is in that core and what, therefore, must be the starting point of all his own search for the right course of conduct for himself.

As a rough rule to find what, in a given field, lies within the core of the known, one seeks to discover in what particulars, say, nine-tenths of the recognized and competent authorities in any given field are in agreement. Wherever there is that kind of agreement among the high-minded, competent and recognized students of a field, there is not one chance in a thousand that they are wrong. This particular bit of knowledge, then, with all its inevitable implications can be taken as a safe guide to one's own thinking and acting, including one's voting.

Now, the subject of physics, in which the core of the known is probably larger than in any other field, furnishes the finest possible illustrations of the rational, scientific method of going at all our problems. To take but one simple example, three hundred years ago the law of gravitation was completely unknown, and all kinds of fantastic and superstitious theories were current as to the causes of the apparent motions of the moon and the planets, and the influences of the positions of these bodies upon our lives. Today all these superstitions are gone among thoughtful and intelligent people. No other subject begins to be as fundamental and as rich in its illustrations of the meaning of the rational mode of approach to life.

I was so impressed with the possibilities of educating the whole of the oncoming generation in these fundamentals, now that so large a fraction of it is in the secondary schools, that I discussed with some of my friends the possibility of getting into the curriculum of the schools in some way a book on *the social significance and implications of physics*. Among us we concluded it was too grandiose a project, involving too big a change in curriculums, for immediate realization, but Professor Gale and I tried to put the idea into effect in a small way in the last rewriting we made of our *Elements of Physics*.

Up to the present, however, let us admit that our universal educational system to the age of about seventeen has not realized at all this first objective of universal education, namely, the job of providing 51 percent of intelligent voters in the United States. Nevertheless, this much is certain: The physics teacher of the future has here an enormous opportunity which I am confident that in time he will grasp and act upon.

I have discussed with some educators a simple plan which, it seems to me, would be at least a beginning in the right direction. Without attempting to change the curriculums of the schools at all, the suggestion is to utilize the weekly assembly in all secondary schools for a series of movies, which would go in succession into all the schools of the country, presenting elements from the cores of *established knowledge* upon which there is general agreement, and avoiding all controversial matters, thus trying to provide a basis for the straight thinking of the whole of the coming generation of American voters. Physics would, of course, have to furnish its full share of the illustrations of the rational, scientific approach to life as distinct from the emotional, the prejudiced, the superstitious approach. If once every week during high school years practically the whole of the oncoming generation could be thus exposed in an interesting way merely to the most basic and unquestioned truths that *have*

been discovered and are now here ready to serve as a guide to the thinking and acting of each one of us, the basis would be laid for getting a 51 percent intelligent vote. The school teacher has the power to accomplish this in 25 years in the United States. Some physics teacher may have the energy and the brains to meet in this or some other way the great opportunity which our universal educational system now provides for educating America up to the opportunities and possibilities of the democratic, American way of life.

A Wind Tunnel for Student Experiments and for Demonstrations

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The need for an inexpensive wind tunnel to demonstrate effectively the flow of an air stream past variously shaped objects, to show the effect of streamlining, to make the streamlines visible, and to measure the lift and drag with ease and reproducible results, led to the development of the apparatus described here. The cost, exclusive of the labor, of the completed tunnel was less than $25.00. The return-type tunnel was selected to prevent the air stream from being blown throughout the room and to allow the use of confetti or chemical fumes such as $TiCl_4$ in making the streamlines visible without the disagreeable effects experienced with the open type. The support of the various objects and of the balance used to measure lift and drag is greatly facilitated by the open testing chamber of this tunnel; and, at the same time, maximum visibility is provided for class demonstrations. The tunnel serves as an excellent piece of demonstration apparatus as well as the basis for a student experiment in the measurement of lift and drag.[1]

The tunnel, Figs. 1 and 2, is constructed of galvanized stovepiping and elbows 12 in. in diameter with the entrance cone constricted to 8 in. The inside of the exit cone is rounded off with plaster of Paris, and immediately beyond this is placed a ring of "breather holes." Several vanes are fitted into the elbow beyond the "breather holes." These vanes are necessary to reduce the backwash in the testing chamber and assist greatly in removing disturbances from the air stream. The entrance cone is preceded by a comb in the form of a grill of 2-in. square openings, the grill being made of sheet iron 2 in. wide fitted within the tunnel. Several fins placed in the elbow just preceding the comb aid in straightening out the air stream. The air stream flowing through the testing chamber is found to have practically a constant speed over its entire cross section. According to a communication from the National Advisory Committee for Aeronautics, the relation

$$d = d_1 + 0.18L \tag{1}$$

should exist between the diameter d of the exit cone, the diameter d_1 of the entrance cone and the distance L between the cones, or the length of the testing chamber.

The propeller, a standard four-blade ventilating type fan 12 in. in diameter, is mounted on a steel shaft operating in bearings adjustable for proper centering. Step pulleys on the shaft and on the $\frac{1}{3}$-hp motor are connected by a V-belt, thus allowing for changes in the speed of the air stream. The propeller rotates in a wooden form which can be opened for adjustments and oiling.

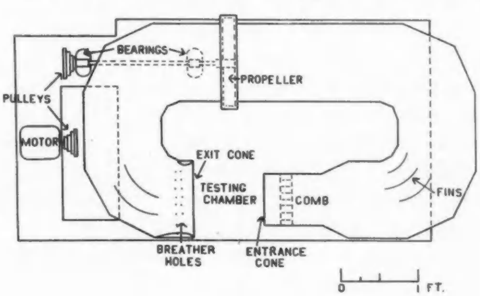

Fig. 1. Top view of wind tunnel.

[1] A larger wind tunnel of the open type is described by S. R. Williams, Am. J. Phys. (Am. Phys. T.) 3, 7 (1935).

The blade tips revolve in a close fitting groove in this form to a depth of about $\frac{1}{4}$ in. This is necessary to prevent excessive leakage of air backward around the blade tips caused by the higher pressure in front of them. The entire assembly is mounted on a reinforced plywood base and is easily moved about.

The balance, Fig. 3, used to measure the lift and drag consists of two arms of equal length fastened at right angles to each other. A scale pan is fastened at one end of each arm. This assembly is mounted in a horizontal plane on a vertically supported pivot. A ring fastened to the lift arm surrounds the horizontal rod supporting the pivot, thus preventing excessive motion in any direction during the adjustment periods. The rod supporting the objects to be placed in the air stream is fastened to this ring. The rod sup-

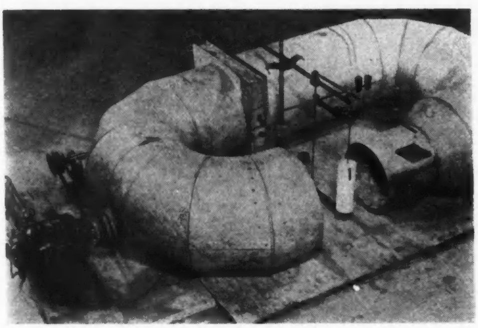

FIG. 2. Photograph of wind tunnel and balance supporting the rotating cylinder.

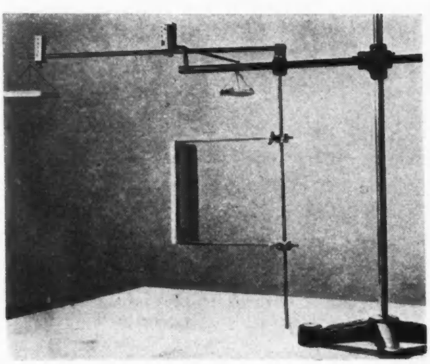

FIG. 3. Photograph of the balance with an airfoil attached.

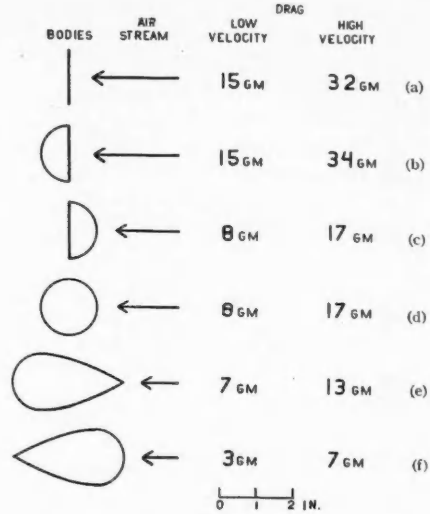

FIG. 4. Cross sections of various objects presented to air stream with values of drag for two air-stream speeds. The objects are: (*a*) flat disk, (*b*) hemisphere, made by cutting a ping-pong ball in half, with flat side toward air stream, (*c*) hemisphere with flat side away from air stream, (*d*) ping-pong ball used as a sphere, (*e*) teardrop with pointed end toward air stream, (*f*) teardrop with pointed end away from air stream.

porting the balance assembly is attached to an upright rod fastened to the plywood base near the propeller housing. The pivot and scale pans are above the tunnel and are easily accessible. Counterweights allow one to balance the system in still air, the fiducial mark being placed on the base directly below the support rod. With this type of support, drag is measured by placing weights on the scale pan fastened to the arm parallel to the air stream while lift, which is a sidewise force caused by the mounting of the object, is measured by the arm perpendicular to the air stream. This mounting proved very satisfactory, readings being easily reproduced to within several tenths of 1 percent. A protractor is attached to the support rod when data as a function of the angle of attack are to be obtained.

The drag experienced by objects of various shape is illustrated by using four objects, Fig. 4, that present the same cross-sectional area to the air stream. They are: (a) flat disk, (b) hemisphere, made by cutting a ping-pong ball in half, with flat side toward air stream, (c) hemisphere with flat side away from air stream, (d) ping-

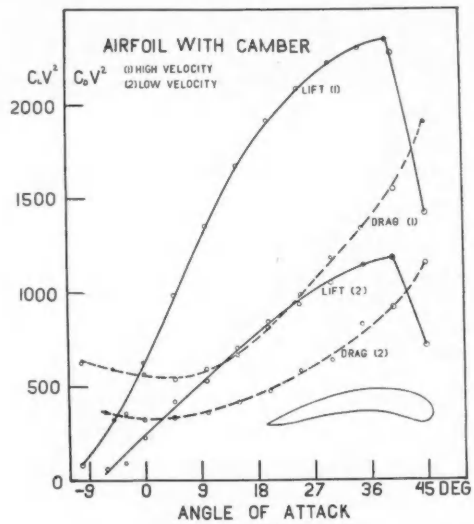

FIG. 5. Variation of lift and drag as a function of the angle of attack for two air-stream speeds. Airfoil with camber, cross section is given in lower right-hand corner.

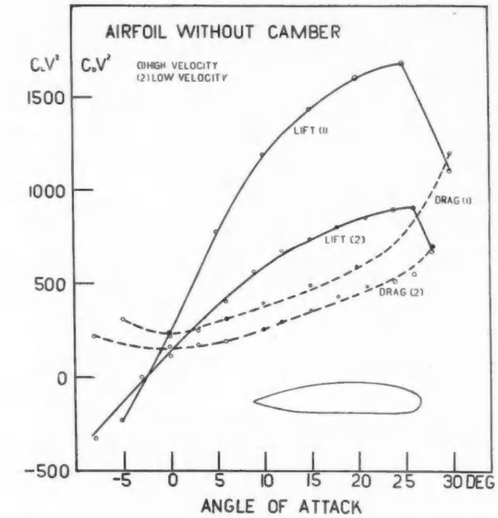

FIG. 6. Variation of lift and drag as a function of the angle of attack for two air-stream speeds. Airfoil without camber, cross section is given in lower right-hand corner.

pong ball used as a sphere, (e) teardrop with pointed end toward air stream, (f) teardrop with pointed end away from air stream. Lift and drag are illustrated by two airfoil sections (shown in cross section in Figs. 5 and 6), one with camber, the other without, made from wood and provided with rods allowing them to be fastened to the support rod. The lift on a rotating cylinder is illustrated by constructing an assembly, Figs. 2 and 7, consisting of a cylinder that can be rotated by a small electric motor such as is used to drive model locomotives. This assembly is fastened to the support rod of the balance.

Figure 4 illustrates the cross sections of the objects exposed to the air stream and values of the drag for two air speeds. Figure 5 gives the product of the lift and drag coefficients and the speed squared for an airfoil with camber for two speeds as a function of the angle of attack. The angle at which stalling occurs is quite evident. Figure 6 gives the results for an airfoil without camber. These values are obtained by using the equation for lift,[2]

$$L = C_L \cdot \tfrac{1}{2}\rho \cdot SV^2, \qquad (2)$$

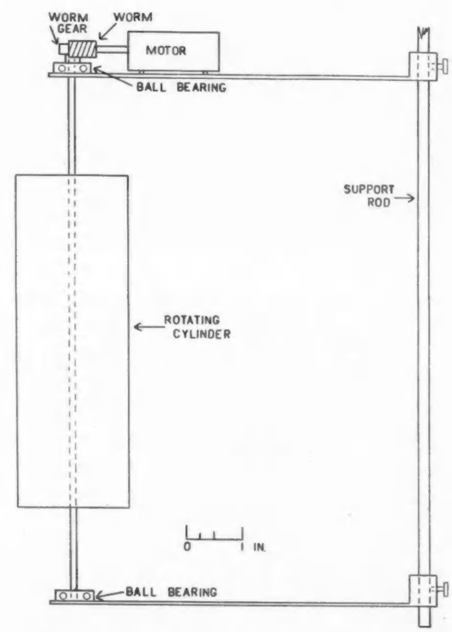

FIG. 7. Cross section of the assembly and method of support for measuring the lift on a rotating cylinder.

and the equation for drag[2]

$$D = C_D \cdot \tfrac{1}{2}\rho \cdot SV^2, \qquad (3)$$

[2] Wood, *Technical aerodynamics* (McGraw-Hill), pp. 10–12.

TABLE I. *Lift on rotating cylinder for various rotational speeds.*

Speed of Rotation (rev min^{-1})	Lift (gm)
94	5
410	10
570	12
640	11

where L is the value of the lift as obtained from the balance, C_L is the lift coefficient, ρ is the density of the air, S is the area of the airfoil surface, V is the speed of the air stream, D is the value of the drag as obtained from the balance and C_D is the drag coefficient. Table I shows the lift placed on the scale pan for various speeds of the rotating cylinder.

The streamlines may be effectively demonstrated by introducing confetti or chemical fumes such as those produced by $TiCl_4$ into the tunnel. A single or small number of streamlines may readily be produced by allowing one or several strings to act as wicks to conduct the $TiCl_4$ into the air stream.[3] These strings are fastened to the ends of small-bore glass tubes inserted vertically to various depths through the casing just behind the comb. The $TiCl_4$ is then dropped into the open end of the glass tube and allowed to evaporate from the string.

[3] This method was suggested to us by Mr. Vernon Andrews, Middlebury College.

A Simplified Method for Verifying the Stefan-Boltzmann Law of Radiation and Determining the Stefan Constant

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IN 1879 J. Stefan,[1] upon examining the values obtained by Tyndall for the energy radiated from a platinum wire at 1200°C and at 520°C, noticed that the energy radiated at these two temperatures was approximately proportional to the fourth power of the absolute temperature. He made the assumption that the radiation between two bodies varied as the difference of the fourth power of their absolute temperatures, and found that it satisfied the experimental results of Dulong and Petit.[2] In other words, if the absolute temperature of a body is T_1, and that of its surroundings is T_2, the total emissive power W, or energy radiated per unit time and per unit area, is

$$W=\sigma(T_1^4-T_2^4),$$

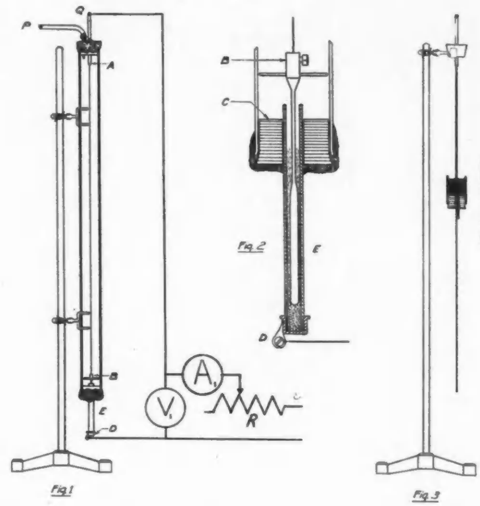
where σ is a constant.

This simple and convenient law rested at the time of its formulation on a rather weak experimental foundation: first, because it was not known whether the nature of the radiating surface played any role and second, because the temperatures were merely estimated. In fact, we know today that the agreement of Tyndall's values with the Stefan law was purely accidental; there was mutual canceling of the errors introduced by the highly selective nature of the radiation from polished platinum and in estimating the temperature of the wire. The agreement of the law with Draper's observation of the intensity of radiation from a platinum wire was due to errors in estimating the temperature of platinum from its expansion. It was not until 1884 that the law was fully established when L. Boltzmann,[3] utilizing Maxwell's ideas of electromagnetic radiation, treated radiant energy inside an enclosure in the same way that a gas is treated as the working substance in a Carnot cycle, and showed that the energy of full radiation from an ideal blackbody is proportional to the fourth power of the absolute temperature.

The precise experimental verification of the "fourth-power law" and the determination of

[1] Stefan, Wien. Akad. **79**, 421 (1879).
[2] Dulong and Petit, "Experiments relative to the rate of cooling mercury in glass thermometers when placed in a vacuum," Ann. Chim. Phys. [2] **7**, 225, 337 (1817).

[3] Boltzmann, Wien. A. **22**, 31, 291 (1884).



the constant of radiation have been the subjects of exhaustive research for a number of decades. The satisfactory solution of the problem involved the construction and the use of (*a*) integral or "full" radiators, that is, bodies capable of emitting full radiation at different temperatures; (*b*) thermometers capable of measuring extensive ranges of temperature with precision; (*c*) radiometers capable of giving accurate relative values of the energy of the emitted radiation. These requirements were approximately satisfied in a number of experiments in which various principles, instruments and methods were employed. For example, J. T. Bottomley, A. Schlerermacher and L. Paschen attempted to test the law by measuring the electric energy dissipated in a platinum wire maintained at a high temperature by means of a current, but, owing to the selective character of the radiation from platinum, failed to obtain results in agreement with the "fourth-power law." The experiments of O. R. Lummer and E. Pringsheim[4] can be considered as the most complete and satisfactory of the early period. Since then, other methods embodying, directly or indirectly, the foregoing principles have been developed, all of which, however, have a common characteristic, that of indirectness of procedure, difficulty of operation and the introduction of correction factors whose values are often difficult to determine. The difficulty of technic involved in controlling a high temperature, in maintaining a surface at a uniform temperature, in determining the total emissive power in absolute units and free from errors due to stray radiation, make this experiment difficult to repeat even in the most fully equipped laboratories. Yet, the Stefan-Boltzmann law, together with the Wien displacement law and its corollaries, has played an important part in the development of theoretical physics, and has found useful applications in the solution of problems extending from those dealing with engineering applications in pyrometry and metallurgy to those of understanding the nature of atoms and stars.

The primary purpose of this paper is to describe a method for (*a*) the verification of the Stefan law by using elementary principles familiar to the students, experimental methods easy to repeat and instruments available in every laboratory; and (*b*) the determination of the Stefan constant of radiation.

The apparatus

The apparatus is represented in Fig. 1. At the axis of a glass cylinder 150 cm long and 4 cm in diameter is suspended a wire AB of known dimensions, which, when electrically heated, constitutes the radiating body. The wire is suspended from a brass or aluminum electrode Q, $\frac{1}{4}$ in. in diameter, which is tightly fitted in a rubber stopper, the stopper in turn being tightly fitted into the upper end of the glass cylinder. A glass tube P passes through this stopper and is connected to an air pump. In the rubber stopper C (Fig. 2) at the lower end of the large glass tube is fitted a metallic tube E, 8 in. long and $\frac{1}{2}$ in. in diameter, which is filled with mercury to the desired level. In this mercury is immersed the electrode B, which is suspended from the lower end of the wire. This arrangement makes it possible to take care of the expansion of the wire, which at high temperatures amounts to several centimeters. The glass tube can be made reasonably airtight by painting the juncture with a mixture of smoking hot beeswax and rosin.

It is most important, obviously, that the surface of the radiating wire behave like a "full

[4] Lummer and Pringsheim, Ann. d. Physik **13**, 395 (1897).

radiator" through a large range of temperatures. Lampblack behaves almost like a "blackbody," as the experiments of Lummer and Kurlbaum indicate, so that the problem was to find a way to apply a thin, uniform coating of lampblack to a wire. After considerable experimentation, a satisfactory method was found for covering the wire with a mixture of ethyl alcohol and lampblack.

The wire to be used as the radiator is cut to the proper length and attached to the upper electrode, which is kept in position as is indicated in Fig. 3. A small glass tube 2 or 3 cm long, one end of which is fitted with a one-hole cork stopper, is slipped over the wire and brought to its upper end. A small wooden wedge placed between the cork and the wire helps to keep the tube in position and to prevent the mixture of lampblack and alcohol, when poured into the tube, from running down the wire. The wire is then cleaned with cotton soaked in alcohol and drawn along the length of the wire without applying unnecessary tension. Finally, the tube filled with the mixture is moved downward (Fig. 3) with a continuous motion. If the mixture is of the right consistency and the tube is moved with the right speed, the wire will be covered with a thin uniform coating. A downward speed of about 1 m/sec was found to be satisfactory, and the best results were secured with a mixture of pure ethyl alcohol and lampblack of considerable fluidity. Once a mixture of the right consistency has been obtained, it is advisable to make a considerable supply of it, so that a uniform mixture will be available for a number of experiments. In case some section of the wire has not been properly covered, the lampblack may be removed and the operation repeated. If a very small area has not been covered, it may be painted with a fine brush.

The lower electrode is now attached to the wire and the latter, after a final inspection for bare metallic areas, especially at the ends, is lowered into the glass cylinder. By attaching cross wires to the lower electrode B, it can be guided into the tube E containing the mercury. After the rubber stopper has been tightly fitted into the glass cylinder the upper electrode Q can be adjusted so that the top of the lower electrode will be at a suitable height above the mercury level (Fig. 2). The cylinder is then made airtight and evacuated to 0.1 mm of mercury, approximately.

The experiment

The electrodes are connected to a source of direct current, a voltmeter, an ammeter and a rheostat (Fig. 1) for the control and measurement of the power used. The current in the wire is gradually increased, and the voltage and current are recorded the moment the wire melts. Assuming for the moment that all of the energy used was radiated from the wire, we have in view of the Stefan law,

$$W = E_1 I_1 = \sigma A_1 (T_1^4 - T_2^4), \qquad (1)$$

where W_1 is the energy radiated, E_1 is the potential difference across the wire, I_1 is the current in the wire, T_1 is the absolute temperature at which the wire melts, T_2 is the absolute temperature of the surrounding space, A_1 is the area of the radiating surface and σ is the Stefan-Boltzmann constant. Since all the quantities in Eqs. (1) either are known constants or can be determined through direct measurements, the equation can be experimentally verified. By using wire of various elements, the law can be verified for a large range of temperatures.

In writing Eq. (1) sources of error have been ignored that must be taken into consideration in a complete analysis of the problem. These are (*a*) energy losses due to convection and conduction of heat by the residual air surrounding the wire; (*b*) losses through conduction of heat from the wire to the electrodes; (*c*) non-uniformity of radiation due to variation of temperature along the wire; (*d*) errors in measuring the true potential difference across the wire. The errors noted in (*a*) are negligible, as will be shown later. The remaining errors can be evaluated and eliminated by a number of methods, two of which will be discussed in this paper.

Method 1.—This method is perhaps the simplest and is direct in the sense that no additional physical principles are involved and the values employed are directly determined. Many experiments made with copper and aluminum wires show that the wires melt with equal probability for all points of the wire to within 4 cm of the electrodes and that there is no special tendency for the wire to break in the middle. From this, it can be concluded that the temperature of the wire is practically uniform, except for a few centimeters near each electrode. This view is corroborated by the fact that the wire occasionally melts simultaneously at two points close to its two ends, and that the bright-

ness of the wire appears to be uniform. Now, if we designate by X the correction for all errors due to the last three causes previously enumerated, Eq. (1) takes the form, for a wire of length l_1 and diameter d,

$$W_1=E_1I_1=\sigma\pi d l_1(T_1^4-T_2^4)+X \qquad (2)$$

and, for a wire of diameter d and length l_2,

$$W_2=E_2I_2=\sigma\pi d l_2(T_1^4-T_2^4)+X, \qquad (3)$$

where X is the same for both equations, since the end-effects are identical. Subtracting Eq. (3) from (2) we have

$$W_1-W_2=\sigma\pi d(l_1-l_2)(T_1^4-T_2^4) \qquad (4)$$

or, if T_2^4 is small with respect to T_1^4,

$$W_1-W_2=\sigma\pi d(l_1-l_2)T_1^4. \qquad (5)$$

Equation (4) or (5) gives the radiation from a wire of uniform temperature and of length l_1-l_2 from which the errors due to the end-effects have been eliminated.

By substituting the accepted value of σ in Eq. (4) or (5), T_1 can be determined,[5] or vice versa. Table I contains typical data for the determination of the melting temperature T_1 of copper. In securing these data the following precautions were taken: (*a*) The percentage expansion of the wire, when its temperature changed from that of the room to the melting point, was determined by observing the displacement of a definite point of the lower electrode relative to a paper scale attached to the glass; this expansion was 2 percent for copper and aluminum; (*b*) the position of the lower electrode was adjusted so that, due to the expansion of the wire, the electrode was just floating on the mercury when the melting temperature was approached (since only a fraction of the weight of the electrode B is not buoyed up by the mercury, the tensile forces acting on the wire are always negligible); (*c*) after the wire melted it was examined to determine whether it was still completely covered with lampblack and, especially, whether both segments were covered with lampblack at the break; (*d*) the diameter of the wire including the thin coat of lampblack, was measured with a micrometer microscope; the value so obtained was increased by 2 percent to obtain the diameter at the moment of melting; (*e*) the electrode B was lifted out of the cylinder by means of a hook fastened to a long rod, attached again to one of the segments of the wire already used, and the whole experiment repeated for the determination of radiation from a shorter wire. Short wires freshly prepared were also used to make sure that the radiating power of the surface was not affected by its previous use. No systematic difference in radiating power was noticed due to the repeated use of the same surface. With short wires either a longer upper electrode or a shorter glass cylinder was used.

TABLE I. *Determination of the melting point T_1 of copper from the relation $T_1=[(W_1-W_2)10^7/\sigma\pi d(l_1-l_2)]^{\frac{1}{4}}$.*

Trial	I_1 (amp)	E_1 (v)	$W_1=E_1I_1$ (w)	I_2 (amp)	E_2 (v)	$W_2=E_2I_2$ (w)	W_1-W_2 (w)	T_1 (°K)
1	12.8	20.2	258.5	12.8	5.20	66.6	191.9	1356
2	13.1	19.6	256.8	13.1	5.55	72.7	184.1	1342
3	13.0	20.5	266.5	13.0	5.60	72.8	193.7	1359
4	13.1	19.6	256.8	13.1	5.60	73.4	183.4	1341
5	13.2	19.7	260.0	13.1	5.60	73.4	186.6	1347
6	12.9	20.0	258.0	12.9	5.49	70.6	187.4	1349
7	13.0	20.0	260.0	13.1	5.57	73.0	187.0	1348
8	13.0	20.0	259.0	12.9	5.43	70.0	189.0	1351
9	13.0	20.5	263.2	13.1	5.60	73.4	189.8	1354
10	12.8	20.2	260.6	12.9	5.36	69.1	191.5	1357
Av.	13.0	20.0	259.9	13.0	5.50	71.49	188.4	1350

$\sigma=5.73\times10^{-5}$ erg cm^{-2} deg^{-4} sec^{-1}; diameter d of both the long and short wires $=3.26\times10^{-2}$ cm; length l_1 of long wire $=130.2$ cm; length l_2 of short wire $=33.6$ cm.

TABLE II. *Determination of the melting point T_1 of copper.*

Trial	I_1 (amp)	E_1 (v)	$W_1-E_1I_1$ (w)	I_2 (amp)	E_2 (v)	$W_2-E_2I_2$ (w)	W_1-W_2 (w)	T_1 (°K)
1	9.40	22.5	212	9.45	6.01	57.6	154.4	1346
2	9.45	22.4	212	9.50	5.92	56.2	155.8	1351
3	9.50	22.6	215	9.50	6.05	57.5	157.5	1353
Av.	9.45	22.5	213	9.48	5.99	57.1	155.9	1350

Diameter d of both long and short wires $=2.7\times10^{-2}$ cm; $l_1=130$ cm; $l_2=33.3$ cm.

In Table I are given the values obtained for the melting temperature T_1 of No. 28 copper wire from Eq. (5) on the assumption that the coated wire was a "full radiator." Although some values of T_1 vary as much as 1 percent from the accepted value, the average value of 1350°K differs only 0.44 percent from the accepted value of 1356°K. The diameter of the

[5] Obviously, to prove the "fourth-power law," it is not necessary to know the value of σ, but only the melting points of some metals.

wire was also measured with a micrometer caliper after it had been used and the lampblack coating had been removed. The value so obtained was of the order of a few thousandths of a millimeter smaller than given in the tables for No. 28 wire. This variation was probably produced in handling and heating the specimen. It must also be stated that the values obtained with the micrometer microscope were accurate only to 0.01 mm, and that in calculating the temperature this must be taken into consideration. If an allowance of 1 percent error in estimating the diameter of the wire is made, the value of the melting temperature will vary by 0.25 percent.

Some results obtained with No. 30 copper wire are given in Table II. They are consistent with those given in Table I, although there is a slight tendency toward higher temperature values than those obtained with No. 28 copper wire. When No. 26 copper wire is used, the tendency is toward somewhat smaller values. These differences, perhaps, may be attributed to the difference of structure of the black surface on wires of different diameters.

TABLE III. *Determination of the melting point T_1 of aluminum.*

TRIALS	I_1 (AMP)	E_1 (V)	$W_1=E_1I_1$ (W)	I_2 (AMP)	E_2 (V)	$W_2=E_2I_2$ (W)	W_1-W_2 (W)	T_1 (°K)
1	12.3	8.59	105.6	12.3	2.67	32.8	72.8	942
2	12.3	8.61	105.9	12.3	2.60	32.0	73.9	945
3	12.2	8.56	104.5	12.2	2.55	32.1	73.4	943
4	12.3	8.54	105.0	12.3	2.54	31.3	73.7	941
5	12.0	8.56	102.7	12.2	2.51	30.6	72.1	939
6	12.2	8.52	103.9	12.2	2.51	30.6	73.3	945
7	12.2	8.33	101.6	12.2	2.49	30.4	71.2	935
8	12.1	8.53	103.1	12.2	2.50	30.5	72.6	940
9	12.1	8.45	102.2	12.1	2.48	30.0	72.2	939
10	12.1	8.51	103.0	12.1	2.68	32.4	70.6	933
Av.	12.18	8.52	103.8	12.21	2.55	31.17	72.58	940

Diameter of both long and short wires $=5.35\times10^{-2}$ cm; $l_1=130.2$ cm; $l_2=33.6$ cm.

Typical results obtained with No. 24 aluminum wire are given in Table III. The average temperature of the melting point of aluminum was found to be 940°K. If, by using Eq. (4), we take into consideration the effect of radiation of the surrounding medium whose temperature was 316°K and which in this case cannot be considered negligible, the value of the melting temperature of aluminum as determined here is 943°K, or about 1 percent above the accepted value of 933°K. Some of these observations were made with the interior of the glass tube coated with lampblack.

The high value of the melting point of aluminum possibly could be attributed to several factors, such as impurities in the wire, a thin film of aluminum oxide[6] on the wire or the lag of temperature attained in the wire with respect to the measured electric energy.[7] Finally, the conduction through the residual gas, however small, must be a contributing factor; it becomes relatively small at high temperatures, as in the case of copper, in view of the predominance of the effect of the "fourth-power factor."

Method 2.—The second method is not as direct and intrinsically precise as the first, but has certain advantages, especially if one wishes to make use of additional principles of physics and to give students the opportunity to evaluate physical situations that cannot be directly measured.

This method will be illustrated in connection with measurements on No. 28 copper wire. When the heated wire was observed in a dark room, its brightness was seen to be uniform to a point 1.6 cm from each electrode and then to decrease, becoming cherry red and just visible at a point 0.8 cm from the electrode. Now, the incipient red heat visible to the average observer[8] is about 550°C, and, in view of the fact that the surrounding space was not dark, owing to the illumination from the incandescent wire, it is safe to assume that the temperature in the middle of the end segments was about 600°C. From the value of the resistivity for this temperature, the average resistance r for these segments was determined and the energy W' dissipated in these segments was calculated from the relation $W'=I^2r$. The value of W' so determined, for the two segments of total length $l=3.2$ cm, was found to be practically 4 w. Corrections for the drop of potential due to the resistance of electrodes, connecting leads and various contact effects are made by determining the drop of potential for various values of the current when the electrodes are directly connected by a short copper wire of negligible resistance. This correction e for the electrodes when thus connected amounted to 0.4 v.

In view of the foregoing considerations, we obtain for the energy W radiated from the uniformly heated segment of the wire,

$$W=(E_1-e)I_1-I_1^2r=\sigma\pi d(l_1-l)T_1^4,$$

where l is the total length, and r the total resistance, of the end segments of the wire, and e is the drop of potential

[6] Aluminum oxide melts at 2050°C.

[7] In determining the lowest temperature at which the aluminum wire could be seen to glow, it was noticed that, after adjusting the current to a definite value, considerable time would elapse before the wire began to glow.

[8] In these experiments it was found that young persons generally were able to see the glow at lower temperatures.

in the electrodes, etc. The foregoing equation can be written in the form

$$T_1=\left[\frac{(E_1-e)I_1-I_1^2r}{\sigma\pi d(l_1-l)}\right]^{\frac{1}{4}}.$$

Substituting the corresponding values from Table I, we obtain for the temperature

$$T_1=\left[\frac{\{(20.0-0.4)(13.0-4\}10^{12}}{(5.73)(3.14)(0.0326)(130.2-3.2)}\right]^{\frac{1}{4}}=1354°\mathrm{K},$$

a result that is in close agreement with the value obtained by the previous method. Actually this method, with the results cited, was used in this series of experiments before method *1* was developed. The value for the melting point of aluminum was found by method *2* to be 943°K.

Additional experiments

By dividing the value of the energy radiated by the wire when it is bare by the corrected value of the energy radiated when it is covered with lampblack, we obtain the emissivity of the metal at its melting temperature. This calculation can also be carried out for other temperatures, provided the temperatures in question are determined either by measuring changes in the resistance of the wire or by measuring its thermal expansion. A few preliminary values of emissivities are given in Table IV. Corrections have been made for the end-effects, equality of radiating area, and the reflectivity of lampblack, which has been taken to be 1.2 percent.

Note that, by this method, it is possible to determine the emissivity of copper and other metals at high temperatures, which otherwise is impossible owing to the oxidation of their surfaces. The value 0.29 for the emissivity of copper is, perhaps, slightly too high, because some elements of the wire were inevitably oxidized from the residual oxygen. The emissivity of cuprous oxide was found to be 0.50. However, this is the value for a particular type of surface and particular color. Higher values were obtained when the surface of the wire had a deeper red hue. Consequently, specific values, such as 0.54, given in tables for the emissivity of cuprous oxide at the melting temperature, should always be qualified. The emissivity of aluminum, whose surface most probably was covered with a thin layer of aluminum oxide, was found to be 0.49. The importance of the accurate determination of emissivity of metals and their oxides in connection with pyrometry and metallurgy cannot be overemphasized.

The Stefan radiation constant

The student who examines the various methods used in the past for the determination of σ will be impressed with the experimental difficulties involved in the use of delicate and

TABLE IV. *Emissivities at melting temperatures.*

Material	Length (cm)	Diameter (10^{-2} cm)	Energy Radiated (w)	Emissivity
Copper with lampblack	127.0	3.26	253.8	1.00
Copper	127.0	3.26	74.1	0.29
Cuprous oxide	127.0	3.26	126.6	0.50
Aluminum with lampblack	123.8	5.35	95.9	1.00
Aluminum oxide	123.8	5.35	47.0	0.49

expensive instruments under physical conditions that are difficult to reproduce, and with the discrepancy of results obtained by experienced observers. The literature on this important subject covers abundantly the various methods and results. It is sufficient to mention here that some of the values of σ determined by recognized observers, differ from one another by as much as 7 percent even after all justifiable corrections have been made.[9] Using the values from Table I and taking the melting temperature of copper as 1356°K, we find that σ is 5.66×10^{-5} erg cm^{-2} sec^{-1} deg^{-4}. This value, however, is based on the assumption that lampblack radiates as an ideal "blackbody." Although many past determinations were made on this assumption, present indications are that lampblack cannot be considered as perfectly black. Coblentz,[10] by direct measurements, has found that the loss by reflection of receivers covered with lampblack was 1.2 percent. Now, in view of Kirchhoff's law, we may say that if we restore to any radiating body the radiation which escapes it by reflection, it will radiate as a "blackbody." Consequently, if we consider that the average radiating power listed in Table I represents 98.8 percent of a blackbody radiation, and if we revaluate the radiation constant on the basis of full radiation, we obtain $\sigma=5.70$ erg cm^{-2} sec^{-1} deg^{-4}, which differs only by 0.52 percent from the accepted value. Here it must be noted that, except for this use of the value of the reflectivity

[9] Some of these values, expressed in terms of the unit 1 erg cm^{-2} sec^{-1} deg^{-4}, are: Kurlbaum (1898 and 1912), 5.45×10^{-5}; Todd (1909), 5.48×10^{-5}; Keene (1913), 5.89×10^{-5}; Coblentz (1915), $(5.72\pm0.012)\times10^{-5}$; Gerlach (1920), 5.80×10^{-5}. Birge, Rev. Mod. Phys. **1**, 1–73 (1929), gives as mean experimental value $\sigma=(5.735\pm0.01)10^{-5}$.

[10] Coblentz, Bur. Stand. Bull. **9**, 283 (1913), found the same reflectivity as when lampblack was painted over platinum black.

of the lampblack, this method is free from any assumption or other corrections, unless they are corrections concerning precision of direct measurements. Also, it must be noted that if this correction in the radiating power of lampblack is made in calculating the melting temperature of copper the average value obtained in Table I will differ by only 0.13 percent from the accepted value.

In calculating T_1 or σ we have assumed that the energy losses through convection or conduction are negligible. This view is justified by the following experiments. First, using No. 26 aluminum wire, it was found that the energy radiation measurements remained constant when the pressure was below 1 mm of mercury. Second, the fact that the values obtained for the melting temperature of various copper wires varied less than 1 percent when their radiating area was varied 58 percent indicates that the effects of thermal conduction must be small. The same may be said when we consider the small discrepancies in the value of σ obtained from measurements with aluminum and copper wire whose temperatures and radiating areas differed by 31 percent and 100 percent, respectively. In any case, this source of error can be made definitely negligible by the use of appropriate equipment.

Some of the advantages of the present method are obvious if we consider that the radiator, the thermometer and the radiometer of other methods are replaced here by a wire of known melting temperature. The error in determining the efficiency of the wire as a "full radiator" is not greater than that in determining how good an absorber is a radiometer in the other experiments. In addition, the measurement of radiation in absolute units, as made in the other methods, is a much more difficult part of the problem than that of securing a good approximation to a "full radiator." In the present method the measurement of the energy radiated is reduced to simple voltmeter and ammeter readings. As for the radiating surface, lampblack is a better radiator than the platinum black used in some of the standard methods, and the texture of the surface remains unchanged owing to the lack of oxygen inside the cylinder. Of course, the problem of making corrections for the radiation absorbed by the atmosphere between radiator and receiver does not exist here. Since the melting temperatures of the principal elements have been determined by a number of thermometric methods, including in some cases direct comparison with gas thermometers, the precision of the values of temperatures used for the determination of σ are well within the order of precision attainable for the other factors, provided the specimens used are reasonably pure.[11]

By using a wire whose diameter has been carefully checked for uniformity, a better vacuum, newly calibrated electrical instruments of proper range, and, finally, a micrometer microscope of considerable power, it should be possible to obtain a basic experimental value of σ in still closer agreement with the experimental average of all other methods.

The writer has tried these experiments with selected groups from three classes of sophomore engineering and science students with satisfactory results, with respect to both experimental performance and grasp of the meaning and significance of the experiment.

[11] To avoid any doubt concerning the actual temperature of the lampblack surface, it is essential to have the thinnest possible coating on the metal. The most uniform and satisfactory results apparently are obtained when the coating is only a few hundredths of a millimeter thick, so that the surface of the wire appears, under the microscope, to have a slight metallic luster with a suggestion of gray in it.

Physicists Needed for National Defense Work

IN an effort to obtain more applicants, the closing date for receipt of applications for civil service examinations for physicists has been extended to December 12, 1941. The positions to be filled are: *physicist* (any specialized branch), $3800; also *principal*, $5600; *senior*, $4600; *associate*, $3200; *assistant*, $2600.

Applicants must have completed a 4-year college course; for the three higher grades they must have had major study in physics; and for the two lower grades they must have completed at least 24 semester-hours in physics. They must have had professional experience in physics, but partial substitution of graduate study in a specialized branch of physics may be made. Applicants will not be required to report for examination or take any written test; they will be rated on their qualifications as shown in their applications and on corroborative evidence. Further information and application forms may be obtained from the Secretary of the Board of U. S. Civil Service Examiners at any first- or second-class post office, or from the U. S. Civil Service Commission, Washington, D. C.

Demonstration Apparatus for Lissajous Figures

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For demonstrating Lissajous figures one usually employs two tuning forks equipped with mirrors, the frequencies of the forks being adjusted by weights on the tines. These adjustments cannot be made continuously or while the forks are in operation and, therefore, are likely to take considerable time, with the result that one usually shows only a single figure during a lecture. Moreover, the angular amplitude of the mirrors is apt to be small. This article describes an apparatus in which the frequency of one oscillator is *continuously variable while in motion;* its convenient optical system, and the simple, direct measurement of the frequencies of the two oscillators is also described.

Continuous Frequency Adjustment

Although the oscillators do not differ essentially from those described by Fertel and Stephens,[1] our apparatus (Fig. 1) has a different optical system

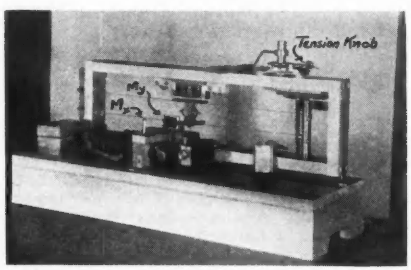

Fig. 1. Photograph of apparatus.

and must, therefore, be arranged differently. One oscillator is a heavily loaded tuning fork of large amplitude with its tines in a horizontal plane; the frequency of this fork is adjusted to exactly 30 cycles/sec. The other oscillator consists of two horizontal piano wires carrying a common load of about 50 gm at their midpoints. These wires are mounted, one above the other, in a strong frame; the frame is parallel to the fork axis. At one end of the frame is a common tensioning device for adjustment of the frequency. The other ends of the wires are held by piano pegs set in the frame, to provide initial tension in the wires. The common load has an armature on its upper face; immediately above this, and fastened to the frame, is the driving coil. Projecting downward from the lower end of the load is a short piece of steel wire (in contact with the lower wire) which is the contactor; it makes contact with a mercury cup of adjustable height, which is fastened to the frame.

Direct Measurement of Frequencies

An impulse counter can be connected to either oscillator by means of a key. A variable resistance in series with the counter is adjusted for the smallest current that gives good operation. For the measurement of the frequency of either oscillator, the counter and its resistance is placed in parallel with the corresponding driving coil and its resistance. When the counter is so connected to the fork, it does not affect the current or frequency of either oscillator appreciably; but when it is connected to the piano wires, then the frequency of the wire oscillator is changed. Accordingly, a substitute coil S (Fig. 2), of inductance equal to that of the counter, is normally in parallel with the driving coil of the wire oscillator; when the frequency of this oscillator is to be measured, the key substitutes the counter for the coil S.

To manipulate the counter, we employ a Western Electric telephone switchboard key, No. 136-A, the lever of which operates either one of two SPDT switches. Figure 2 shows the connections when the key is in the neutral position.

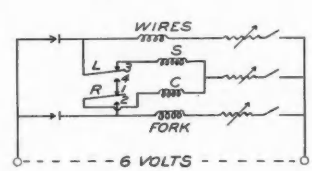

Fig. 2. Wiring diagram.

[1] Fertel and Stephens, Am. J. Phys. (Am. Phys. T.) **5**, 223, (1937).

When the key is pushed in one direction, blade L moves from *3* to *4* and puts the counter, with its rheostat, in parallel with the driving coil and rheostat of the wire oscillator, thus substituting the counter for S. When the key is pushed in the other direction, blade R moves from *1* to *2* and connects the counter to the fork-driving coil, S being left in parallel with the other driving coil. With this arrangement the counter may be disconnected or connected to either circuit without any visible effect on the Lissajous figure.

The Optical System

Straddling the fork, near the middle of the piano wires, is a bridge on which are mounted two mirrors, as in Fig. 3. Mirror M_x imparts horizontal motion to the light spot on the screen and is therefore mounted on a vertical axis; it is connected to the fork. Mirror M_y gives a vertical motion to the spot, is mounted on a horizontal axis and is connected to one of the piano wires. Each mirror frame has an arm about 8 cm long.

Figure 4 shows how M_x is attached to the fork. To the weight on one tine is fastened a stiff wire, bent up at its free end; the arm of M_x is held against the vertical portion by a small rubber band. The arm of the other mirror is held against one of the piano wires, also by a rubber band. The angular displacement of M_x is equal to the linear displacement of the end of the fork (nearly) divided by the length of the mirror arm; by making the wire long and the arm short, the

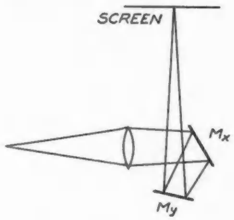

FIG. 3. Mirror system.

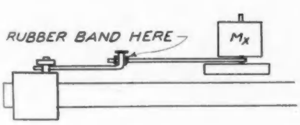

FIG. 4. Method of attaching mirror M_x to fork.

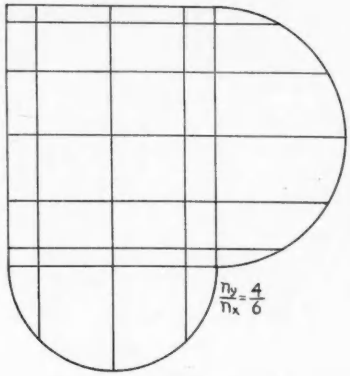

FIG. 5. Drawing for lantern slide.

angular displacement of the mirror may be made very large.

Figure 3 shows that any light which passes by the side of M_x does not reach the screen. If an opaque wall screen is used, the class sits on the same side as the apparatus; if the screen is coated with luminescent paint, there is no objectionable flicker from the low frequencies employed in this apparatus. One can also use a translucent screen, the class sitting on the other side.

Obviously a number of frequency ratios can be quickly demonstrated with this apparatus. When a stationary pattern is obtained, it can be quickly identified,[2] and the findings can be checked by an actual frequency count.

Geometrical Construction of Lissajous Figures

Several drawings like Fig. 5 were made and photographed to lantern slide size. The *negatives* were then made up as slides. When such a slide is projected on the blackboard, one can draw in rapid succession the various figures possible with the corresponding ratio of frequencies. The second of the two rules given in the article referred to in reference 2 can be deduced with such a drawing.

[2] Gaehr, J. Opt. Soc. Am. and Rev. Sci. Inst. **18**, 490 (1929).

To be *appreciative* of the merits of science is something more than to be *merely impressed* by its achievements—R. E. Lee, *Man the Universe Builder*.

A Study of Secondary School Physics in Pennsylvania

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AND

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WHILE the world is becoming more technically minded, its organization always more and more based on the machine, and the principles of physics ever more basic for life, interest in physics in the schools seems to be on the decline. Some enrolment figures are available. The United States Office of Education[1] states that in 1910 physics was studied by 14.6 percent of high school students and in 1928 by 6.9 percent. Again, with the high school enrolment from 1922 to 1928 increasing by 35 percent the enrolment in physics increased only 3 percent.[2] Also by 1934 physics enrolment was down 6.3 percent.[2] In Pennsylvania in 1938–1939 only 5 percent of the total students enrolled studied physics.[3] These are but a few of the indications pointing to the need for a critical survey of the high school situation. Obviously college physics teachers should not remain aloof from this problem.

A recent survey[4] of physics teaching in the high schools of a particular Pennsylvania county involved certain findings that seemed to indicate the value of pursuing the study over a state-wide area, and such a project has been undertaken.[5]

The information was obtained by sending a questionnaire to a sampling of public high school physics teachers in the state. This method has obvious drawbacks, but in the present case no other method without insuperable work presented itself. To obviate any such uncertainties as usually follow the questionnaire, the authors made a generous sampling—40 percent—and took unusual care to get a large response. All but 3 percent eventually responded. Diverse approaches were necessary to secure a 97-percent response. As a last resort, a letter to the nearest college physics department, requesting help, was effective in a few cases.

Schools were arranged for sampling according to enrolment in 11 enrolment classifications, from 0–199, 200–399, 400–599, and so forth, to the final classification of 2000 or more, and in each classification alphabetically according to counties. Then every first, fifth, sixth, tenth, and so on school was chosen, which would make 40 percent in the ideal case if the total of each classification was divisible by 5. Actually, by

Table I. *Distribution of general questionnaire and percentage of returns.*

Enrolment	No. of Schools	No. of Questionnaires Sent	No. of Questionnaires Returned	Percent Returned
2000–	37	15	14	93
1800–1999	11	4	3	75
1600–1799	8	4	4	100
1400–1599	12	5	5	100
1200–1399	15	6	6	100
1000–1199	32	13	13	100
800–999	37	15	15	100
600–799	78	31	31	100
400–599	120	48	45	94
200–399	188	74	73	99
0–199	367	147	141	96
Total	905	362	350	97

this method, out of 931 high schools in Pennsylvania, 362 were chosen, which, in addition to the 26 schools of Cambria County included in the preceding study[4] made a total of 388. Of these 388 questionnaires, 376 were returned. See Table I.

Of the latter, 22 were not usable because, in 15 cases, physics had been discontinued, and in 7 cases, a new teacher was involved who was teaching chemistry in a school where the two sciences alternated, and thus had not yet taught physics. Of the 12 questionnaires not returned, 6

[1] F. M. Phillips, *Statistics of Public High Schools*, 1927–1928, U. S. Office of Education Bull. 1929, No. 35.

[2] Jessen and Herlidy, *Offerings and Registrations in High School Subjects*, 1933–1934, U. S. Office of Education Bull. 1938, No. 6.

[3] C. D. Morneweck, Chief, Child Accounting and Research Div., Dept. of Public Instruction, Harrisburg, Pa. Personal letter, May 28, 1940.

[4] M. H. Trytten, "A study of secondary school physics," Am. J. Phys. **8**, 154 (1940).

[5] The actual survey was carried out by the junior author; see J. M. Leach, *Status of Physics Teaching in Pennsylvania High Schools*, thesis submitted to the Graduate School of Arts and Sciences of Duke University, 1940.

TABLE II. *Percentage of upper grade students in physics.*

	All Schools	0–199	200–399	400–599	600–799	800–999	1000–1199	1200–1399	1400–1599	1600–1799	1800–1999	2000–
Senior Enrolment*	34,208	2830	3340	3769	4397	2483	2900	1223	1589	1311	989	7170
No. of juniors and seniors studying physics	12,034	1691	1406	1290	1825	802	860	512	509	211	128	1797
Percent studying physics	35	60	42	34	42	32	30	42	32	16	13	25
Group percent**		60	38		30							

* Number of seniors is used to indicate the number of students in the stream of students passing through the upper grades, and affords a reasonable base for the percentages.
** The enrolment of the small high school is considered to be less than 200; medium-sized high school, 200–599; and the large high school, 600 or more.

TABLE III. *Percentage of girls studying physics.*

	All Schools	0–199	200–399	400–599	600–799	800–999	1000–1199	1200–1399	1400–1599	1600–1799	1800–1999	2000–
No. of juniors and seniors studying physics	12,034	1691	1406	1290	1825	802	860	512	509	211	128	1797
No. of girls enrolled in physics	3,177	686	466	419	424	225	166	132	92	23	11	330
Percent of physics enrolment that girls constitute	26	41	33	32	23	28	19	26	18	11	9	19
Group percent		41	33		21							

TABLE IV. *Number of students enrolled in vocational or industrial physics.*

		Size of School										
Percent	Total	0–199	200–399	400–599	600–799	800–999	1000–1199	1200–1399	1400–1599	1600–1799	1800–1999	2000–
No. in physics	13,513	2496	1992	1344	1984	664	860	512	509	211	128	1661
No. in vocational physics	1707	91	139	41	419	30	85	95	163	—	24	343
Percent	13	4	7	3	21	5	10	19	32	—	19	20
Group percent		4	5		18							

represent schools of lowest enrolment (0–199) and 4, schools in the next two classifications. The other two were among the largest schools (about 2000). Thus in the middle-size group the response is complete. Five of the small schools not answering were in the hard coal region of Pennsylvania where education has been attended by grave financial difficulties. If these schools exist they may have discontinued physics.

Status of Physics in the Schools

Since high schools are organized with a varying number of grades, all enrolments in physics are here calculated as percentages of the number of seniors in the schools, regardless of the year in which physics is offered. If physics is offered every other year, half of this enrolment is used. With this understanding the small schools enrolled 60 percent, the medium-sized schools 38 percent, and the large schools 30 percent, where small schools are those having 0–199 total enrolment; medium-sized schools, 200–599; and large schools, 600 or more. In Pennsylvania the total high school population falls into these three classifications about in the ratios 1 : 2 : 4. The enrolments of girls in physics courses in the same groups were 41 percent, 33 percent, and 21 percent (Tables II and III).

The enrolment in vocational, or "related," physics is increasing, especially in the large schools. Of the total physics students enrolled, 13 percent were studying this type of course.

In the smaller schools having a total enrolment of 600 or less, 5 percent of the physics enrolment was in this type, whereas it was 18 percent in the schools above 600 (Table IV).

Although the higher enrolment in physics in smaller schools is probably due to the fact that a small school cannot offer such a diverse choice of courses, it should be borne in mind that in such schools, for the same reason, physics may be dropped. The low percentage of students in small schools who go on to college, as shown in the next paragraph, would indicate that these schools are very likely to turn away from physics as not being "practical" for noncollege people.

Since there has been considerable discussion as to whether the school physics course should be college preparatory, information as to the probability of a college career was inserted in the questionnaire. The results show that 82 percent of the high schools send less than 50 percent of their graduates to college, 46 percent send less than 20 percent, and 68 percent send less than 30 percent. Of the small schools, 82 percent send less than 30 percent to college; of the medium-sized schools, 69 percent send less than 30 percent, and of the large schools 48 percent send less than 30 percent. The indication is that as the school becomes larger, a greater proportion of the students become college material, a fact that may be significant when it is recalled that in the larger schools the physics enrolment is proportionately less. It would be of interest to know whether the greater percentage of college material in larger schools is due to the urbanization of the more intelligent or merely to increased opportunity for those in larger centers of population. Nineteen percent of all physics students in small schools, 23 percent in medium-sized schools, and 31 percent in the large schools intend to go to college; or, taking all physics students together, 22 percent plan to enter college.

Physics is elective in 86 percent of the schools, required in 6 percent, and required for the academic, vocational and scientific courses in 8 percent.

Mathematics is a prerequisite to physics in 62 percent of the schools. Broken down into groups, the results show 70 percent of the small schools, 57 percent of the medium-sized schools, and 51 percent of the large schools requiring mathematics as a prerequisite. Of those requiring mathematics, 52 percent require algebra I only; the others require, in addition, usually plane geometry, although some require algebra II, or general mathematics. Upon this matter of a mathematics prerequisite the maximum disagreement seems to exist.

A majority of the teachers indicated that they were aware that many of their students would not attend college after graduation. Fifty-two percent endeavored to adapt their courses to the noncollege student, while only 36 percent asserted that their courses were definitely college preparatory. Of the remaining 12 percent, half met the problem by separate courses, while the rest answered with a variety of responses that indicated some attempt to meet the needs of the noncollege group as well as the college group.

Where separate courses were offered, the noncollege course seemed to lean toward the vocational. Unfortunately, one could not go into the precise difference between a college preparatory and a noncollege preparatory course without unduly loading the questionnaire. It is entirely possible that the difference is mainly one of pressure or intensiveness. An attempt was made to probe into this point when speaking with certain teachers but with little satisfaction. One of them frankly confessed that, when under supervision, he made a great show of teaching "vocational" physics by having so-called "practical" material about, but when not supervised he broke away and taught just "physics." The emphasis on the noncollege student was much more marked among the smaller schools. Here only one in four claimed his course to be college preparatory, whereas among the larger schools one in two was the approximate ratio.

The Teachers

Information about the teaching loads, subjects taught, preparation, experience, and so forth was considered a most important objective of this study. Only 6 percent of the teachers teach physics alone. Actually 4 percent is a more accurate figure, since only 14 teachers, all in schools of approximately 1000 enrolment or more, and 7 of them in the very largest schools

TABLE V. *Frequency with which other courses are taught with physics, based on the number of periods per week.*

Course	Periods per Week	Course	Periods per Week
Chemistry	1212	Geography	102
General science	956	Social science	98
Mathematics	913	Vocational agriculture	71
Biology	795	English	56
Senior science	193	Shop	40
History	184	French, electricity, German, first-aid, safety, mechanical drawing	84
Physical education	116		
Health	112		
Total			4932

* Chemistry labs included ratio, 2 laboratory periods =3 class hours.

of 2000 or more, taught physics exclusively. Of the other 6 making up the 6 percent, 5 are in the small schools (0–199) and are also either principals or coaches. Sixty-five percent of the physics teachers in small schools are either principals or coaches.

TABLE VI. *Activities in which physics teachers participate.*

Activity	Number of Teachers: Total No.	Per-cent	Small Schools	Medium Schools	Large Schools	Cambria County
Science club	58	12	10	24	19	5
Other clubs	82	17	30	22	23	7
Athletics	114	23	62	24	18	10
Administrations	107	22	35	39	23	10
Publications	17	4	8	4	3	2
Music	15	3	5	8	1	1
Dramatics	19	4	8	5	4	2
Miscellaneous	24	5	7	8	8	1
None	50	10	14	15	20	1
Total	486*	100	179	149	119	39
No. of teachers	368		131	111	99	27
No. in activities	318	86	117	95	80	26
Percent sponsoring activities			90	86	81	96
Median hours per week per teacher**			6.5	4	5.2	4.2

* Many teachers had more than one activity.
** This group of figures doubtful since many teachers failed to estimate.

Twenty-three percent of physics teachers teach physics with one other subject; 31 percent teach it with two other subjects; 24 percent teach it with three other subjects; and 16 percent teach it with four or more other subjects. As an indication of how the size of the school affects this phase, 71 percent of the teachers in small schools, 32 percent in medium-sized schools and 11 percent in large schools teach physics along with three or more subjects (Table V). In order of frequency the subjects taught most often as a single subject with physics are chemistry, general science, mathematics, biology and senior science. Again in order of frequency, combinations which occurred as subjects taught by physics teachers where two additional subjects were taught, are chemistry-biology, chemistry-general science, general science-biology, general science-mathematics, chemistry-senior science, chemistry-mathematics, and general science-senior science.

Consequently it would seem that for a prospective teacher of physics, a minor field should be some science other than mathematics. Teachers were asked to comment on the combinations of courses they were teaching. Thirty percent expressed dissatisfaction. Of these, 42 percent were in small schools, 28 percent in medium-sized schools and 19 percent in large schools. In stating their preferences they were practically unanimous for combinations involving only science and mathematics. Twenty-one teachers did not care to teach physics, preferring in order of frequency, mathematics, chemistry,

TABLE VII. *Classification of teachers according to undergraduate credit in physics.*

Semester hrs of Undergraduate Credit in Physics	Total: No.	Percent	Size of School: 0–199	200–399	400–599	600–799	800–999	1000–1199	1200–1399	1400–1599	1600–1799	1800–1999	2000–
30 or over	20	5	3	3	1	—	2	—	1	—	1	1	6
24–29	24	7	5	4	4	2	1	1	1	1	1	—	1
18–23	54	16	22	7	3	8	3	1	1	1	1	—	3
12–17	97	28	32	19	17	9	5	5	—	1	—	2	1
6–11	131	38	57	28	11	10	3	4	1	1	—	—	5
1–5	14	4	7	4	1	1	—	—	—	1	—	—	—
None	7	2	1	1	3	—	—	1	—	—	—	—	1
Total	347	100	127	66	40	30	14	12	4	5	3	3	17
Group Median	13		12	13		15							

chemistry-biology, social studies, biology and a few scattered courses.

A rather significant picture is presented by the analysis of duties other than teaching. Eighty-six percent of all physics teachers have extra-teaching activities. Seventy-nine different activities were listed, many of which could be classified as administrative, athletics, etc. Table VI gives a fair idea of this side of the teacher's life. In the small school, particularly, a great deal of time goes into this form of activity. Sixty-five percent of the physics teachers in the small schools are principals, coaches, or both; the figure drops to 32 percent in medium-sized schools and to 17 percent in the large schools.

Table VII gives a composite picture of the physics preparation of the teachers responding to the questionnaires. It will be noted that 44 percent have 11 semester-hours or less. Eleven hours means very little more than one college course, since physics is taught as a 10-hour course in many colleges. Adding a second course of three or four hours per week for a year gives a total in the neighborhood of 14–16 hours. The table shows that 72 percent have had no more than this. In many schools 24 credits are considered a major. Only 12 percent have this much. Strangely enough the relation between teacher preparation and size of school is less marked. The median preparation varies only slightly in favor of the large school. Obviously the large schools should be able to select the better prepared teachers, and such is the case but not to the extent that might be expected.

Only 16 percent of the physics teachers have had any graduate work in physics. Nine percent of the teachers in the small schools, 17 percent in the medium-sized schools, and 26 percent in the large schools have had graduate work in physics. Only 4 percent, however, have had as much as 10 credits. Of these, over half were in the schools of 2000 or more enrolment. When nonphysics work is included the results are different: 51 percent of the teachers have more than 15 hours of graduate credit; 31 percent have master's degrees; 15 percent have had no graduate work. The obvious conclusion is that a teacher taking further work after entering the teaching profession most likely will study something other than physics. Usually he takes courses in education.

The majority of teachers have had less than 6 years of experience. The median length is 5 years. Teachers with longer experience were in the large schools or were doing administrative work.

Laboratory Work

The advisability of laboratory work as a part of high school physics has come under question. Many educators lean toward the demonstration method of teaching as a substitute, and so do many administrators, because of the difficulties offered by the laboratory in the way of cost, teacher time, and schedule fitting. The question and the trend have been discussed frequently of late, for example, by Levelle and Curtis.[7]

In the questionnaire the teachers were asked bluntly, whether, in their opinion, laboratory work of the old, individual type was necessary to the understanding of physics. Eighty-six percent answered "Yes."

The majority of all schools spend less than \$75 per year on equipment. Forty-one percent of the largest schools spend less than \$50 per year. About 50 percent of the teachers, particularly in the small schools, feel that their equipment is insufficient for good experimental work.

Very little individual laboratory work is done. More than half of the schools report large groups of from four to seven or more working on the same experiment. The single laboratory period predominates. Seventy-eight percent have one or two periods per week, while 9 percent have no definite period. The larger schools tend to the shorter periods. The rule is large laboratory sections, especially in the larger schools.

Specifically, 56 percent of the schools have a laboratory period of 40 to 60 min, or about one period. Practically all of the remaining schools reported approximately $1\frac{1}{2}$ hr. Only 5 percent reported 2-hr periods. One or, at most, two periods per week is the rule in 78 percent of the cases. Only 10 percent have three or more periods. The laboratories tend to be crowded. The group median for small schools was 18

[7] J. M. Levelle, "The laboratory pro and con," Sci. Counselor **39**, 643–644 (1939); F. D. Curtis, "Some effects of the depression upon the teaching of science," Sch. Sci. and Math. **34**, 347–348 (1934).

students in a laboratory section. For the medium-sized schools the median was 21, for large-sized schools, 28. Of schools having more than 2000 enrolment, 87 percent had more than 30 in the laboratory classes.

In 25 percent of the cases it was claimed that laboratory preparation required no outside time; 40 percent spent one hour per week; 19 percent two hours; and the rest up to five hours per week and more.

Special Questionnaire

A special group of 21 teachers, chosen because, in point of preparation and experience, they seemed the best qualified of the complete group, was sent a second series of questions, and all answered. Although it would seem that no better group could be chosen to speak for the high school physics teacher, their responses indicate some confusion in thought regarding the proper status of physics in the high school.

The opinions of these specially chosen men follow:

(*a*) An intelligent understanding of one's environment and some familiarity with the scientific method seem to be main objectives of the physics course.

(*b*) The declining interest in physics is due to the fact that physics is taught from an academic, rather than a utilitarian, point of view, and to the fact that a more and more diversified offering of courses is drawing more and more students into other fields.

(*c*) As to content, these teachers feel that less mechanics and more electricity, sound and light would be an improvement. Yet they add that more automobile mechanics would be a good thing.

(*d*) A majority feel that girls should not avoid physics.

(*e*) Considerable division of opinion exists as to the content of the textbook. Some feel that much mathematical and drill material should be eliminated and applied physics introduced, but no clear majority opinion exists here.

(*f*) The physics course is almost unanimously declared too difficult. More demonstration and less emphasis upon the engineering aspects were declared necessary. This is not too complimentary to the American student or his training.

(*g*) The majority recommend senior science to the nonspecializing student.

(*h*) More than one physics course should be given, that is, liberal arts and vocational.

(*i*) The expense of the course is no great obstacle. The difficulty of scheduling the laboratory is a grave one. It is forcing the one-hour laboratory upon the teacher, and this is proving so inadequate that the tendency is to substitute demonstrations or class cooperative experiments. The teachers feel that this is not a suitable substitute and actually reduces interest in the course.

Conclusion

Only certain main results of the study could be included here. Since the authors have had many requests for a copy of the study, a special, more extended, mimeographed report has been prepared and is available.

In summary the following points seem indicated:

(1) Physics in the high schools of Pennsylvania is on the defensive.

(2) The trend is toward a "useful" course, and with the high schools constituted as they now are, this may militate against the science.

(3) More people study physics in the small school where the course is still traditional in character.

(4) The teachers are inadequately prepared.

(5) The average teacher teaches more of something else than physics and hence his principal interest is possibly elsewhere.

(6) Large classes, heavy loads and outside activities leave the teacher too little time to prepare interesting laboratory work and effective demonstrations.

Emergency Grant-in-Aid for Physics Publication Program

THE American Institute of Physics has for several years been greatly indebted to the Rockefeller Foundation for encouragement and financial assistance in developing a well-rounded and normally self-sustaining publication program in the field of physics. A drastic decline in foreign dues and subscription income caused by the war in Europe has now threatened to cancel the gains which have been made. In response to the Institute's appeal on this account, the Foundation has generously granted the sum of $20,000 to assist the Institute to adjust the publication program to the new circumstances. At a meeting on November 22, 1940, the Executive Committee of the Institute Governing Board passed a resolution in which it expressed appreciation of this timely and generous assistance and conveyed to the Rockefeller Foundation an assurance of the gratitude of physicists.—H. A. B.

The String Model in Geometrical Optics

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STRING models to represent mathematical surfaces have had wide use. Specific adaptation of the method offers advantages for instruction in geometrical optics, where the strings may be used to represent light rays. Models, illustrating a subject inherently as precise as geometrical optics, merit precision in design and construction. While often the physics lecturer can teach effectively with "rough-and-ready" equipment, demonstration aids designed precisely and constructed carefully should not be undervalued.

The five models, Figs. 1 to 5, are roughly similar in dimensions, about 20 in. in length and 6 or 7 in. wide and high, and have general structural features in common. The framework is aluminum, in four main pieces: the floorpiece, braced beneath by angle iron, and three uprights attached to this at either end and in the central region. The uprights at the ends supply the object plane and a screen plane, respectively. Into the central upright is fitted a set of transparent celluloid cross sections to indicate the type of lens. The frames are finished in matt white. The strings are heavy silk threads. Somewhat heavier linen thread, marked to give the appearance of a dashed white and black line, represents the optical axis.

The models are made to scale from exact measurements with actual lenses. However, the axial and the transverse scales are preferably not the same, both for structural practicability and for instructional emphasis. In fact, the axial scale itself can be changed locally, as in the chromatic aberration model, where the separations of the foci for different colors are greater, relatively, than the corresponding focal lengths.

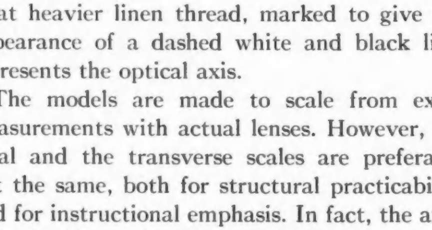


Fig. 1. *Spherical aberration.* Model viewed from above. Screen plane at image position for paraxial rays.

In the two models representing chromatic and spherical aberrations, Figs. 1 and 2, a small bead marks the focus of the rays belonging to a given emergent cone, the strings for that cone being passed through the bead. This device calls attention to the fact that, in the absence at the focus of an intercepting object, such as an image screen, the rays do not stop there, as some diagrams appear to imply, but go on through with their direction and character unchanged.

Spherical Aberration

Threads all of the same color can, when desired, represent rays of monochromatic light of that color, as in the model showing spherical aberration, Fig. 1. Here we have this aberration in the ordinary meaning of the term, that is, axial spherical aberration, with the source of the rays a point located on the axis. Several hollow coaxial cones of rays are shown emanating from the source and incident upon corresponding

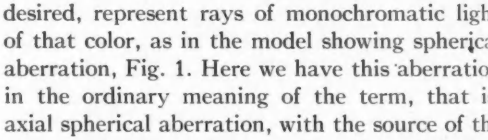


Fig. 2. *Chromatic aberration.* Single outer zone. A dashed-line thread represents the axis.

annular zones of the single thin convergent lens. For the particular plano-convex lens shown, the screen plane was located in the model at the image position for paraxial rays, as found by measurement of the principal focal length and calculation. Although the smallest, or innermost, zone has a diameter only about one-fourth that of the lens itself, its focal point (the bead for which was omitted from the model for mechanical reasons), for the given position of the source, falls appreciably short of the screen plane in the paraxial-image position. This phenomenon can

stand emphasis, especially in general physics, where we become so accustomed to using the simpler abscissa formula, $(1/u)+(1/v)=1/f$, to represent the performance of the lens as a whole, whether corrected or not, that we may fail to emphasize fully its strict limitation to paraxial rays.

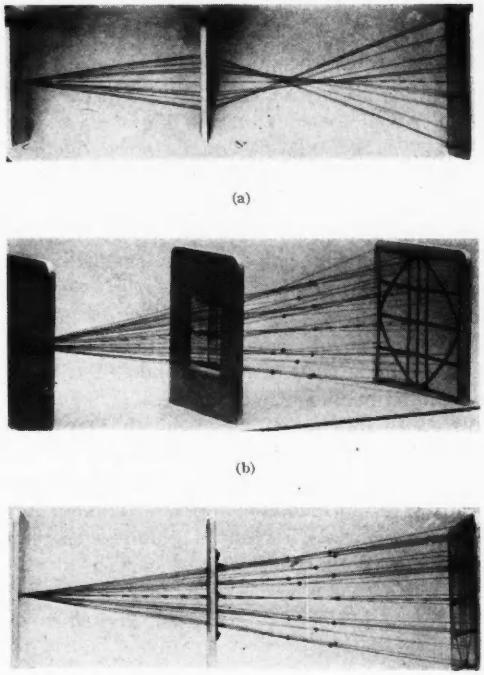
In this particular model, the zones chosen correspond to equal linear separations of the respective images on the axis. If, on the other hand, the zonal radius had been regarded as an independent variable, the axial separations of the images would not have been equal. The shape of the caustic surface is evident.

Chromatic Aberration

Threads of different colors to represent rays of those respective colors are used effectively in a model to show chromatic aberration, Fig. 2. A single hollow cone of red, yellow and blue rays (more specifically, the C, D and F lines, important to the lens designer) are represented as emanating from a point source on the optic axis and incident upon a single outer zone of a thin convergent lens. The red, yellow and blue strings are uniformly distributed in the incident cone, but the three colors are bent different amounts by passage through the lens. An attentive glance at this model should suffice to fix in the memory (1) the greater bending of the blue than of the red, with the yellow intermediate, and (2) the progressive increase in the separation of the axial images as one goes from red to blue, thus emphasizing the physical meaning of the dispersion curve with its characteristic shape.

In this model, representing a crown-glass lens, the distance along the axis between the blue and the yellow axial images is approximately three times that between the yellow and the red, while the ratio of the corresponding wave-length-differences is only about half this amount. A contrast may here be drawn with the so-called "normal" dispersion of a diffraction grating.

Effect on image definition.—With the foregoing models it is easy to show why either a single uncorrected lens or a poorly corrected lens system must give poor definition. Even with monochromatic light, as the first model shows, if the whole lens area is uncovered, the definition will be poor, no matter where we place the image screen. Both models considered together show that if the light is polychromatic and the lens unstopped we cannot possibly have a sharp image even of a point source, although it is on the lens axis.



(a) (b) (c)

FIG. 3. *Astigmatism.* Plano-cylindrical lens. Single "focal line." (a) View from above; the horizontal section shows the maximum power, with spherical aberration. (b) Oblique view from in front of model; beads indicate image positions for different ray-pairs; with the whole lens uncovered, the "focal line" is really a sheet. (c) View from directly in front, showing zero power in the vertical plane, and also, to best advantage, the arrangement of foci of the ray-pairs.

Astigmatism: One Focal Line

When the object point is off the axis, astigmatism and coma enter. Of these two aberrations, astigmatism is the less difficult for students to grasp. The fact that astigmatism in general is characterized by two short "focal lines" separated a finite distance from each other and directed perpendicular to each other and to the chief ray of the pencil of light can be introduced to the beginner through the less complicated performance of a single plano-cylindrical convergent lens, which gives only one real focal line,

Fig. 3. Although a square aperture was employed here, since this was the actual shape of the cylindrical lens from which the measurements were taken, it is obvious that any lens can be cut to have a periphery with any one of a variety of shapes, as witness the evolution in shape of spectacle lenses. The zones, with the single exception of an annular one, are here square to conform to the shape of the aperture.

The convergent power of this lens is different, of course, in different azimuths, being zero—the same as that of a plane-parallel plate—in an axial (meridional) plane containing the cylinder axis, which is vertical in the model, and having a maximum value in an axial plane at right angles to this. In this horizontal plane where it has its maximum curvature, the cylindrical lens performs as would a spherical lens of this curvature, in any of its meridional planes, with a point source on its axis. This horizontal plane is therefore subject to both spherical and chromatic aberration. However, the use of monochromatic light eliminates the former aberration, and thus simplifies this model.

Looking down on the model from above, Fig. 3(a), that is, along the plane containing the cylinder axis, we see plainly in cross section the caustic surface that goes with spherical aberration. If all the lens is uncovered, the line image of the point source cannot possibly be anything but fuzzy. Even if the rays are limited to a pair of linear zones symmetrically placed on either side of the vertical axial plane, the focal line formed is not strictly straight, but bends, in the axial plane, slightly toward the lens, Fig. 3(b). Moreover, for an annular zone only, with light of single wave-length, the focal line becomes a curve with a shape, in the axial plane, suggesting a hyperbola. The shapes of these ray-intersection curves which lie in the vertical axial plane because of the symmetry of the optical system with respect to that plane are best viewed from directly in front of the model, Fig. 3(c).

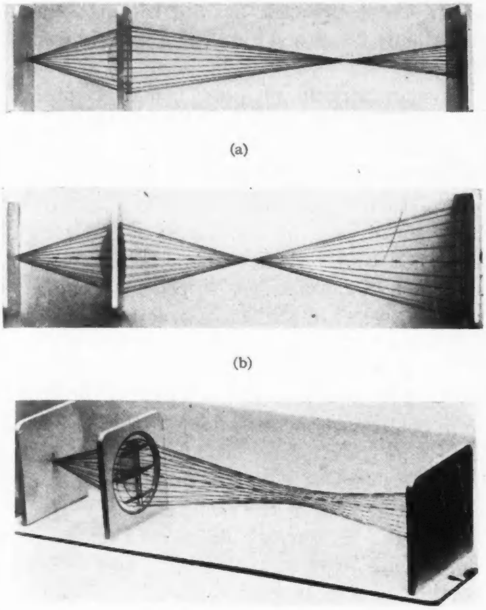
A visual comparison early in one's study of geometrical optics, such as that offered by Figs. 3(a) and 3(c), makes clear the differing performance, for a small axial object, of a *toric type* lens in different azimuths. From this a surer step can be made to the comparative performance of a *spherical* lens in its different planes, both those that are axial and those parallel or oblique to the axis. Figure 3(a) shows the maximum convergence in the horizontal plane of the cylinder, 3(c) the zero effect in the vertical plane where the cylinder acts like a plane-parallel plate.

A study of the cross section of the light beam, particularly the refracted part of it, at places other than the focal or image position, is always interesting and important; for the complete optical performance of a system includes what is going on everywhere, and not simply at that place where we say the "image" is situated. The screen plane in this model was located, not at the "image," but at that distance from the lens where the four boundary rays at the corners of the cross section form a square, Fig. 3(b). The cross section itself is not square, but has a shape suggesting pincushion distortion. The pattern, however, formed on the screen plane by the rays intersecting it, while not an image in the optical sense, is a kind of projection of the strictly linear zones in the cylindrical lens itself. Thus the rays from a straight-line zone in the lens form on the screen plane a representation that is not linear. The straight lines, whether vertical or horizontal, in the lens plane, are all represented on the screen plane by curved lines that bow inward. The one annular zone in the model is represented correspondingly by a figure that is not circular, but roughly diamond shaped, with the sides of the diamond bowing outward.

Furthermore, all the other axial planes, having azimuths intermediate between those of maximum and minimum power, are subject, in gradually lower degrees, to both spherical and chromatic aberration. None of these planes is represented in the model. It is evident then that with all the lens uncovered, and especially with polychromatic light, a really sharply defined focal line is impossible, so that any elementary notion of a well-defined, ideally straight focal line is found untenable, especially with nonparaxial rays.

Astigmatism: Two Focal Lines

Our next step in the demonstration of astigmatism is with a toric type lens convergent in both the azimuth of maximum and that of minimum power. The model, Fig. 4, presents a single lens, spherical on the incident side, cylindrical on the other. The axis of the cylinder is vertical, as in the preceding model. Obviously,



(a)

(b)

(c)

FIG. 4. *Astigmatism*. Sphero-cylindrical lens. Single annular zone. Two focal lines. (a) View of model from in front; second focal line seen in section; vertical plane has minimum power, the convergence being due entirely to the spherical surface. (b) View from directly above the first focal line; precision of construction of the model is shown by sharpness of this line as seen in perpendicular cross section; horizontal plane has maximum power, due to both surfaces of the lens. (c) Oblique front view; circle of least confusion located in the region where the ray-sheet has its small cross section; note the celluloid strips depicting the shape of the lens.

the power of the lens must be minimum in the vertical axial plane, Fig. 4(a), and maximum in the horizontal, Fig. 4(b).

In this second astigmatism model, mechanical complications are avoided by using monochromatic light and only one zone, which is circular. Thus we have a pure "Sturm's conoid," sometimes depicted in books for a rectangular aperture. With a single circular zone, the circle of least confusion is the best "image" obtainable of the point object. It is located about where the refracted beam appears at its minimum cross section in Fig. 4(c). In Fig. 4, especially 4(c), the manner of using celluloid pieces to represent cross sections of a lens is evident. Precision of design and construction is shown by sharpness of the focal lines, seen in cross section in Figs. 4(a) and (b).

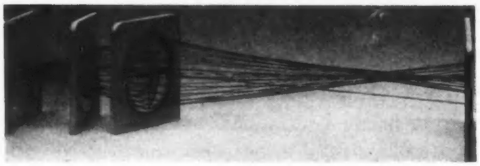
Looking at Fig. 4(c), or even at the model itself from this oblique viewpoint, the casual observer needs a second thought to realize that, in spite of its total appearance due to the really complicated shape of the surface of the Sturm's conoid, each string (ray) goes absolutely straight through from lens to image screen, just as though all the other many strings were entirely absent, and even while making its contribution to the complex curved surface that degenerates in two different places to lines that are perpendicular to each other.

Comments that have been made on the single focal line of the preceding model apply in general to both focal lines of the present one. The lines are not ideally straight, and in general not sharply defined. From these two astigmatism models, it is seen why the focal lines usually have short, finite lengths, these being determined by the diameter of the lens opening, and how they approach nearer to straightness the shorter they are. The optical designer's remedy for this aberration is to get rid of the lines, combining them as far as possible to form a single "point image."

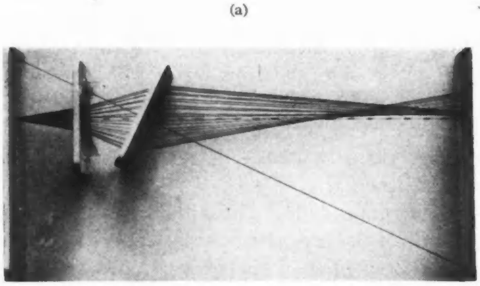
COMA

The fifth model demonstrates coma in a plano-spherical, convergent lens. Since this aberration requires that the point source be off the axis, astigmatism also will be present. To separate out the coma for study by itself, we must neutralize the astigmatism, in other words, correct the lens for it, just as would be done for an eye suffering from this aberration, by adapting a corrective lens. The corrective auxiliary lens here is plano-cylindrical and divergent, since the astigmatism of the convergent test lens is positive. In Fig. 5 the dashed-line string represents the axis of the corrective lens, and the black thread, that of the test lens.

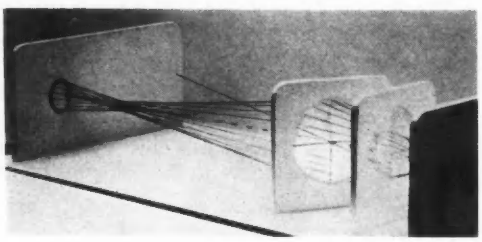
The rays emanate in a hollow cone from a point source appreciably off the axis of the test lens, the cone being determined by a single annular zone of this lens. They pass first through the auxiliary, which in the vertical azimuth, Fig. 5(a), does not change their divergence, but in the horizontal azimuth, Fig. 5(b), increases it



(a)



(b)



(c)

FIG. 5. *Coma.* Point-source off axis (black thread) of the plano-spherical test lens. Axis of auxiliary lens shown by dashed-line thread. (a) Model viewed from side; image is seen not to be a point. (b) From above; horizontal power of auxiliary lens is maximum. (c) Oblique view; cardioidal section of ray sheet is indicated on the screen plane.

a maximum amount. This effect—varying with the azimuth of the axial plane of the auxiliary lens—on the rays incident at the test lens, neutralizes an equal but opposite effect on the rays by the test lens itself—due to its being inclined to the incident beam—thus leaving the emergent beam free from astigmatism.

The remaining aberration is pure coma, except for curvature of the image surface and also distortion, neither of which would affect the appearance of the comatic figure, or "image," of the point source. Chromatic aberration is again absent only because we are using monochromatic light.

A characteristic of pure coma of a single annular zone is that the best obtainable image of the point source is a circle, or ring. A remarkable feature of this ring is that it is double. This is not apparent if the image screen is placed at the ring. Considering the two halves of the test lens as defined by its vertical diameter, if we cover either one of these halves to prevent passage of the rays, we shall still have a complete ring in the image plane. The rays through these two halves of the lens are therefore, for purposes of instruction, represented by strings of two different colors, although the light is monochromatic throughout. A close-up visual inspection of the model thus shows clearly the duplicate character of the image ring of the point source, Fig. 5(c).

The cross section of this pencil of rays as a whole, going away from the image ring in either direction, is seen to be a double loop, with the inner loop diminishing, the outer one enlarging, until the inner loop has shrunk to a cusp, giving a cardioidal shape to the cross section of the pencil. This shape is seen, Fig. 5(c), where the screen intercepts the pencil. The positions of the two sets of rays in this plane are indicated by a painted cardioidal figure in corresponding colors, although the black and white photograph does not differentiate the colors. If we go still farther away from the image ring, either toward the lens or away from it, we find the cusp has disappeared, and that the section becomes eventually a smooth, closed curve without apparent tendency toward the peculiar behavior of coma. But this smooth, elliptical shaped curve near the lens, nevertheless, contains the germ of the remarkable duplicate behavior over the range between the cardioidal planes, with the double circle in the central part of this range.

The authors wish to acknowledge financial assistance from the Department of Physics and to thank Mr. Lewis H. Humason for the pictures of these string models, which are difficult subjects for photography.

I wish to busy myself with permanent relations, and thus give my mind its first experience of eternity.—GOETHE.

Photography in the Physics Curriculum

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THE desirability of including a course in photography among the offerings of a physics department depends much on the character of the curriculum as a whole. Thus at Brown University we did not consider photography seriously until the adoption of a four-course basis for academic work made desirable the introduction of a number of new one-semester courses. The wisdom of monopolizing one sixteenth of a student's college time with photography might well be questioned, whereas one half of that might be spent to advantage. The significance of such a course lies in the opportunity which it provides for attracting students who might not otherwise take physics, and in its value as an introduction to applied physics.

I have never in the past taken a very evangelical attitude toward physics. The years of hard work which lie ahead of a student who expects to enter on a career in physics would almost remind one of Winston Churchill's great perorations dealing with the tasks which face the British people, and, if success is finally achieved, he must find his reward primarily in the satisfactions inherent in the work itself. Nevertheless, with misfortune hovering over the world, it has become only too apparent that the democratic countries are seriously lacking in the type of technical training which physics provides. Ten years ago in Germany I observed physics courses crowded with students, even though they called for attendance five days a week, and even though the lectures began at 8 A.M., well before daybreak in winter. Much has been said and written by sincere liberals regarding the relative importance of science and the humanities, but it is a grim question whether the democracies can survive if they fail to cultivate the sciences to the same degree that they are being nurtured in the more aggressive totalitarian countries; and I must confess that the more intense the hue and cry has been against the evils of a scientific civilization, the keener has grown my own desire to interest able young people in physics.

The task of the physicist is to design and use instruments or apparatus for quantitative measurement, and to handle the data so obtained by graphical or mathematical methods in such a manner as to exhibit the essential features of the phenomena being studied. For three centuries these methods have proved successful in progressively opening up the resources of nature, and have been increasingly used as a guide to new fields and improved methods in industry. The growing tempo of fundamental discoveries in pure physics during the past quarter century has led, it seems to me, to a disproportionate emphasis on this phase of physics as against its technical applications. We have come to depend on the brilliancy of these new discoveries in the atomic realm to enlist the interest of students, and have overlooked the depressing effect of the vague concepts and formidable mathematics inherent in the new theories.

Meanwhile, there has always been operating a tendency to sterilize our curriculum of topics on applied physics. Thus Professor Emeritus Arthur Watson began his career at Brown in the physics department, but transferred to engineering when the applications of electricity to industry gave birth to electrical engineering. Similarly, for a number of years after coming to Brown I gave courses in electric oscillations and thermionics, topics that have since been largely taken over by the engineering division. It is altogether within the bounds of possibility that the rapidly increasing importance and technical nature of photography, now one of our major industries, will lead to the creation of a new field of photographic engineering; and another child of physics, having become of age, will be ready to leave the parental roof.

Although college courses in photography have greatly increased in number during the past few years, they are in no sense innovations. About 1910 a semester course was offered at Harvard, and played an important part in attracting me to a career in physics. The cause of the recent

increase is to be sought not merely in the growing popularity of photography as a hobby and its greater industrial importance but also in the fact that its enhanced technical character makes it a more suitable vehicle for demonstrating physical methods. Photography is a form of graphic art, and as such it must rank as one of our most important mediums for the communication of ideas. I will not dwell on the large proportion of the furnishings of your mental storehouse and mine which we owe to photographic stimuli, but I would like to point out that, like all forms of communication, it has both advantages and limitations. Thus a painter has control of each individual brush stroke, but is limited by the fact that he can make only a finite number of such strokes, and can work with only a finite number of colors. The photographer, despite the limited control which he can exercise over the final character of his picture, has at his disposal what is to all intents and purposes an infinite variety of gradations and colors. The fact that his means of control are limited makes it especially important for him to understand them well and use them skillfully. Photography, like language, may be said to have a "grammar" and a "vocabulary," and only when these are mastered can the individual acquire a "style" that will make his work notably effective as a means for communicating his ideas. The purpose of the college course in photography is to teach this "vocabulary" and "grammar."

As examples of the essentially physical character of most problems in this field, consider three different aspects of the photographic process: the drawing of the image, the filling in of the picture with gradations of light and shade and, finally, the reproduction of color. The drawing of the image is the function of the lens. Since time immemorial the elements of lens optics have been considered a significant part of the elementary physics course. As the subject matter of the latter has become more and more crowded by the addition of new material, it has become progressively more difficult to find the necessary time to handle satisfactorily even a minimum of geometrical optics. A course in photography provides an opportunity to develop this rather fascinating subject at sufficient leisure to make it of real value. For one thing, the fiction of a thin lens can be dropped, and emphasis can be placed on the simple universal properties of the well-corrected anastigmats that are so generally used in photography. I would like to point out in this connection the great advantage of transforming the lens formula into the simpler Newtonian form

$$pq=f^2,$$

where p and q are the object and image distances, measured, not to the lens itself, nor to the Gauss points, but to the principal foci. This form has the advantage of measuring all distances to points that are readily determined experimentally. Furthermore, with the short focus lenses so generally used today, the distance p, measured to the front principal focus, is roughly equal to the distance to the lens itself, and q, measured from the rear principal focus, is simply the displacement of the lens from its infinity position. Practically all of the calculations which are necessary in photography can be carried out more simply with this formula than with the traditional one.

A well-corrected lens is designed to reproduce accurately a subject that lies entirely within a plane perpendicular to the lens axis. Unfortunately it is usually called on to form a two-dimensional reproduction of a three-dimensional object. Such an attempt brings at once into the limelight a fatal defect of the lens as a drawing instrument. In compensation for the speed with which it performs its task, we must accept its inability to focus simultaneously on more than a single plane. To be sure, we can decrease the amount of diffusion present in the images of points off this plane by decreasing the lens aperture. This, however, entails the necessity of giving the lens a longer time in which to perform its task, and by diffraction causes a reduction in the sharpness of the image in the focal plane itself. The factors involved here are singularly reminiscent of the uncertainty principle. Sharpness in the reproduction of points that lie within the plane which is most sharply focused seems to be irreconcilable with sharpness in the images of points that lie off that plane. The role which focal length plays in this problem is interesting. It is easily shown that, when photographs are taken from the same viewpoint with lenses of different focal length and are enlarged (or reduced) to the

same final size, the depth of field will be the same if and only if the diameters of the apertures are equal. It is well known, however, that the resolving power of a lens depends only on this diameter, and it will accordingly be the same whenever the depth of field is the same. This is a special though practically important case of a very general theorem to the effect that, whenever in photographing an object with an optically ideal lens any procedure is adopted to increase the depth of focus, it will by diffraction decrease the sharpness of rendition of the subject material in the plane of optimum focus.

The reproduction of three-dimensional objects in two dimensions also leads to difficulty in perspective. Form may be severely misrepresented, and the size of objects will appear correct only if the final print is viewed from such a distance that the angle which it subtends is equal to that included by the original subject. The choice of aperture, focal length, and the relative position of lens and film must often involve compromises which take into account such items as perspective, the state of rest or motion of the subject, and the comparative significance of material at different distances from the camera. Marvelous as the lens is for drawing purposes, it must be used with full appreciation of its capabilities and limitations.

As we turn to the reproduction of gradations of light and shade, we encounter problems that can no longer be solved by such a simple expedient as exploring the consequences of known optical laws. What shall we mean by the correct reproduction of light and shade? Must the brightness of the image on the photographic print be equal to the brightness of the subject? Perhaps, if it is to be considered a perfect reproduction; but such a requirement is unreasonable since the brightness of the print will depend on the intensity of the illumination, which is seldom under complete control. If this ideal requirement is given up, might we still demand that the brightness of the various image areas be *proportional* to that of the corresponding areas of the subject? Perhaps, but since the brightness ratio of the lightest to the darkest area of a photographic paper is at most about 50 to one, subjects with larger ratios of light to shade could not be so represented. We are thus led to consider the possible adequacy of a representation in which the image brightness is proportional to some power of the subject brightness, or, in other words, a representation in which the logarithm of the image brightness is a linear function of the logarithm of the subject brightness. Owing to the logarithmic response of such sensory perceptions as vision, this type of reproduction will represent as equal those gradations that appear equal to the eye; and the satisfaction of this requirement has been accepted as adequate for monochrome photography since the pioneering work of Hurter and Driffield. For color work we must still demand strict proportionality to the first power of subject brightness.

In general, photographic reproduction is a two-stage process, the making of the negative, and of the print. If a graph of the transmission density of the negative *versus* the logarithm of the subject brightness is a straight line, the Hurter and Driffield condition for correct reproduction is satisfied in the first stage. Similarly, if the graph of the reflection density of the print *versus* the transmission density of the negative is linear, the desired condition will be satisfied in the second stage. Both graphs are actually **S** shaped, similar in form to magnetization curves and thermionic tube characteristics, but both are often close enough to linearity in the vicinity of the point of inflection to make excellent reproduction possible over a limited range of values. In the case of the negative there is no reason why the range of brightness that is present in most subjects cannot be included within an approximately straight portion of the characteristic. In the case of the print, however, the full gamut of values from white to black must lie on the **S**-curve, and only those tones in the middle range can possibly satisfy the condition for correct reproduction. Extreme highlights and extreme shadows are bound to be reproduced with deficient contrast, unless the reproduction is restricted to a limited range of grays, a sacrifice of total scale which is not often desirable. This fundamental defect in photography has not always been sufficiently stressed, despite the fact that success in pictorial photography depends in no small measure on the skill of the artist in locating his most significant material in that portion of the characteristic which furnishes the

best possibility of satisfactory reproduction. Filters can often be used to push up the contrast in landscape highlights, but the problem of retaining adequate contrast in the shadows is more difficult to solve. It should be pointed out that the older carbon and platinotype processes and the more recent palladiotype process all have much straighter characteristics than the best of projection papers. The difficulty of highlight and shadow reproduction is best studied by attempting to reproduce a gray step scale in which the values extend all the way from white to black. If the decreased contrast at the ends of the strip does not appear severe in the first reproduction, it can be greatly accentuated by making a second photograph of the first copy. This problem is of more than academic interest. Blocked shadows and washed-out highlights are so nearly universal in photography as to provide a practical means for distinguishing most photographs from other pictures at a glance.

As a third example of the physical nature of many photographic problems, let me make a few closing remarks about color. In 1910, when the course to which I have referred was offered at Harvard, the Lumiere screen plate was the only practical process for reproducing color. Up to 1930 there was still no satisfactory method for making prints. Since then, however, several such processes involving the use of pigments, dyes, or metallic toners have been brought to a high level of perfection, while technicolor and Kodachrome have been dividing the transparency field between them in this country. All of these processes depend on an analysis of the various colors of the subject into their primary color components and the subsequent synthesis of these colors from primary dyes or pigments. This whole fascinating field of color analysis and synthesis is well adapted to treatment in a college course. Instruments such as the Eastman transmission and reflection densitometer are capable of making the most essential measurements, while materials available for the various color printing processes and dye-coupled developers, now also available commercially, can be used for synthesizing the colors. The most serious difficulty which lies in the way of perfect fidelity in color reproduction is the lack of altogether satisfactory primary color pigments or dyes. The best Kodachromes and some outstanding paper prints give an amazing illusion of accuracy, but one has only to attempt, as in the case of the gray scale, a second reproduction of either in order to be impressed with the residual errors.

The reason for the difficulty lies in the fact that even our best magenta primaries absorb a considerable amount of blue, and all bluegreens absorb both blue and green. This makes it impossible to reproduce colors that are purer than these somewhat degraded primaries, and so restricts the gamut of colors which can be obtained. It also places certain difficulties in the way of the automatic duplication of colors which is involved in the photographic technic. Although nothing can be done on paper prints to extend the gamut which a particular set of primaries permits, it is, nevertheless, possible by masking methods to compensate in a measure for the errors that the photographic operations themselves introduce. Complete compensation of this sort would be extraordinarily complicated, but correction for the worst defects is not too difficult, and is playing an increasingly important role in commercial practice. Whereas we must look to the chemist for dye improvements, this masking technic calls for very beautiful densitometric studies of an essentially physical nature, and constitutes an excellent example of the nature and power of the methods of applied physics.

Although the topics chosen for this discussion have been selected with a view to demonstrating the way in which familiar physical procedures can be applied to photographic problems, it should not be forgotten that photography is more than just another dusty corner of the field of physics or chemistry. It is the most modern and perhaps today the most important branch of graphic art. Just as tools that the physicist has provided in the form of thermionic tubes and amplifying circuits have contributed vastly to a wider appreciation of music, so photography is now contributing in a similar fashion to a more general understanding and appreciation of graphic art, and physics is again seen to be making contact between the scientific and the cultural aspects of our modern civilization.

Reproductions of Prints, Drawings and Paintings of Interest in the History of Physics

15. Reproductions from the Manchester Town Hall

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MUNICIPAL buildings are usually of little professional interest to physicists. A notable exception, however, is the Town Hall of Manchester, England, whose main entrance lobby is shown in Plate 1. The beautiful white

PLATE 2. Statue of DALTON in the main entrance lobby of the Manchester Town Hall.

PLATE 1. Main entrance lobby of the Manchester Town Hall, showing statues of JOHN DALTON and JAMES PRESCOTT JOULE.

PLATE 3. Statue of JOULE. He holds in the hand a model of his apparatus for determining the mechanical equivalent of heat.

PLATE 4. JOHN DALTON Collecting Marsh-Fire Gas. [From the mural painting by Ford Madox Brown.]

statues on each side are those of JOHN DALTON (1766–1844) and JAMES PRESCOTT JOULE (1818–1889). Front views of these statues are shown in Plates 2 and 3. That two scientists should thus be given the places of honor in the chief public building of one of the principal manufacturing cities of the world speaks well not only for the effect that these two men had upon the life of the community in which they lived and worked but also for the sound culture of the rest of the citizenry.

Several of the mural paintings in the Great Hall, or auditorium, of this unusual town hall are also of considerable scientific interest. These murals, 12 in number, depict the following events in the history of Manchester: "The Romans Building a Fort at Mancenion," A.D. 60; "The Baptism of Edwin," A.D. 627; "The Expulsion of the Danes from Manchester," A.D. 910; "The Establishment of Flemish Weavers in Manchester," A.D. 1363; "The Trial of Wyclif," A.D. 1378 "The Proclamation Regarding Weights and Measures," A.D. 1556; "Crabtree Watching the Transit of Venus," A.D. 1639; "Chetham's Life Dream," A.D. 1640; "Bradshaw's Defense of Manchester," A.D. 1642; "John Kay, Inventor of the Fly Shuttle," A.D. 1753; "The Opening of the Bridgewater Canal," A.D. 1761; "Dalton Collecting Marsh-Fire Gas." They were executed by FORD MADOX BROWN (1821–1893), one of England's greatest historical painters, and are perhaps his greatest achievement. The one of "Dalton Collecting Marsh-Fire Gas" is reproduced in Plate 4.

The Teaching Effectiveness of the Sound Motion Picture "The Electron"

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THE writer has described a technic[1] by means of which a study can be made evaluating specifically:

(1) The learning produced by two showings of a film;
(2) The effect of an additional stimulus to learning in the form of a study sheet to be used during the class hour when the film is shown.

The relative effectiveness of the two methods of presentation was evaluated by measuring:

(1) The acquisition of factual material;
(2) The ability to transfer new learning to specific new situations not used in the film;
(3) The learning differences characteristic of the various ability levels;
(4) The differences in the learning of specific items produced by two methods.

This technic was worked out in connection with a study of the Erpi Picture Consultants' film "Electrodynamics."[1]

The vocabulary and the background of general experience of most college students, augmented by an understanding of the elementary facts about magnetism and electrostatics, are the prerequisites assumed for the film "Electrodynamics." On the other hand, the film "The Electron" uses a more specialized vocabulary and assumes a more detailed knowledge of electricity and some knowledge of chemistry. It is probably correct to say that the latter film is more highly specialized, more advanced and more difficult than the former. For example, the pre-test and post-test arithmetical mean scores in the electrodynamics study were, respectively, 19.8 and 33.0 out of a possible 47, while the comparable scores for the present study were 11.1 and 21.5 out of a possible 45. Moreover, the gains in this study increase from the low to the high quartiles, whereas in the former one they decreased, owing to the large amount of knowledge about the principles presented by the film which was possessed by the better students before they saw the films. The student groups in the two studies were comparable.

EXPERIMENTAL TECHNIC

(1) The writer and his assistant carefully studied the film through several showings at normal and slow speed. The principles discussed in the script and illustrated by the 52 scenes in

[1] Am. J. Phys. (Am. Phys. T.) 7, 224 (1939).

the film were listed, and 29 multiple-choice items relating to fact[2] were made. Two or three questions involving different approaches were built around some of the more important principles.

(2) A second examination of 16 items was made using the principles in situations quite different from the ones in which they were cast in the film. This examination was intended to measure the student's ability to transfer usefully his information to a new situation.[3]

(3) A study sheet[4] was prepared listing 23 important things to be watched for in the film and suggesting questions whose answers could be found in the pictures. This sheet was given to Section A but not to Section B. In the former study[1] it was discovered that the study sheet directed attention *away from*, as well as *toward*, parts of the film. Consequently, great care was exercised in the construction of the present study sheet. Because of these differences, the evaluation technics worked out and reported before, although essentially the same, vary in some of the details.

TABLE I. *Matching of Sections A and B.*

	A	B
No. of students in the matched groups	52	57
Fact pre-test A.M.[1]	9.115	9.12
Transfer pre-test A.M.	2.21	2.29
Fact pre-test S.D.[2]	3.88	3.84
Transfer pre-test S.D.	2.49	2.56
1st sem. phys. grades A.M.[3]	5.50	5.54
1st sem. phys. grades S.D.	2.25	2.29

[1] A.M. is arithmetic mean.
[2] S.D. is standard deviation.
[3] 4 represents a grade of C −, 5 represents C, 6 represents C +.

TABLE II. *Section matching by quartiles based on semester grades.*

	A	B
Total No. in matched groups	52	57
Quartile I, A.M.	2.77	2.92
S.D.	.973	1.33
Quartile II, A.M.	5	5
S.D.	0	0
Quartile III, A.M.	6	5.78
S.D.	0	.67
Quartile IV, A.M.	8.53	8.71
S.D.	1.44	1.22

(4) On the Friday preceding the week of the experiment, the students in two sections of Liberal Arts College Physics were told that there would be an inventory pre-test on the following Monday, a double showing of the film, "The Electron," on Wednesday and a learning-test on Friday. They were asked to participate on a voluntary basis only, and those who volunteered agreed not to undertake, during the next week, any learning project in college physics other than the regular laboratory work which had little in common with the film.

On Wednesday, five minutes before the film was seen, Section A only was given the study sheet, which carried the instructions: "Look for the following points and for answers to the following questions." The film was shown twice, and during the 10-min intermission, the students

TABLE III. *Comparison of pre- and post-tests.*

	A	B
No. of students	52	57
Pre-test A.M., fact and transfer	11.0	11.193
Pre-test S.D.	5.581	5.44
Post-test A.M., fact and transfer	22.5	20.526
Post-test S.D.	7.087	8.218
Gain	11.5	9.33
Pre- *vs.* post-test correlation	.49±.07	.77±.035

[2] Sample fact finding items:

1. Electricity is composed of: (1) a positive fluid-like charge substance, (2) a negative fluid-like charge substance, (3) a discrete charge of invariable size, (4) discrete positive charges of indefinite size, (5) discrete negative charges of indefinite size.
2. All of the electricity transported in all electrolytic solutions is carried by: (1) free unattached negative charges called electrons, (2) material particles, some (+) and some (−), (3) free unattached positive charges called protons, (4) material particles, all (+), (5) material particles, all (−).
3. When metal atoms are deposited from a solution as pure metal, they: (1) sometimes deposit on the (+) electrode, (2) never deposit on the (−) electrode, (3) sometimes deposit on both electrodes simultaneously, (4) deposit on neither electrode but, being discharged, simply fall to the bottom, (5) always deposit on the negative pole.

[3] Sample transfer items:

1. To double the weight of gold deposited by electrolysis we need to: (1) double the charge transferred, (2) double the current used and the time the experiment runs, (3) double the concentration of the solution, (4) double the area of the electrodes, (5) expose the solution to x-rays sufficient to double the number of ionized atoms.
2. If a glass plate suspended in air is charged either (+) or (−), in order to discharge it rapidly we might: (1) touch the opposite edges with a grounded wire, (2) rub it lightly with a piece of silk, (3) hold it over the flame of a gas burner, (4) rub it lightly with a piece of wool, (5) blow air over it by means of a fan.

[4] Sample study-sheet items: (1) To which electrode do metallic ions go? (2) How are electric current, time and quantity of electricity related? (3) What are the relative weights of hydrogen and silver atoms?

TABLE IV. *Test data (fact and transfer) and correlation for the two groups. Quartiles based on grades in first semester physics.*

QUARTILES	SECT.	PRE-TEST RANGE	POST-TEST RANGE	PRE-TEST A.M.	PRE-TEST S.D.	POST-TEST A.M.	POST-TEST S.D.	CORRELATION, PRE-TEST *vs.* POST-TEST
I	A	3–15	10–27	8.5	3.1	18.6	6.2	+.12±.18
I	B	0–16	6–28	8.8	4.0	13.3	6.4	+.53±.13
II	A	3–28	14–36	11.4	6.1	23.3	7.0	+.51±.14
II	B	1–15	11–23	8.5	3.7	18.1	3.9	+.56±.12
III	A	2–18	14–30	9.8	4.3	21.5	3.9	−.08±.19
III	B	2–20	11–34	11.7	4.3	22.5	7.5	+.72±.08
IV	A	3–25	9–39	14.0	6.3	26.6	6.9	+.29±.17
IV	B	6–29	19–42	15.7	6.0	28.5	5.7	+.92±.03

were asked to examine the study sheet again to see if they had made observations on all of the items listed. Section B observed two showings of the film as ordinarily presented. The students were permitted discussion in the intermission while the film was being rewound.

RESULTS

Fifty-seven students from Section A and 63 from Section B took part in the tests. Of these it was found that 52 from Section A would match 57 from Section B when the pre-test scores were used as a basis of matching. Also these two groups are highly comparable when the first semester grades in mechanics, heat and sound are used as a basis of matching. Tables I and II give data which show the matching on these bases. They show that the two groups were highly matched with respect both to knowledge of the principles presented in the film and to physics aptitude as measured by their first semester grades. Section B has a slight statistical advantage.

The gain as measured by the post-test minus the pre-test results (Table III) shows that Section A made a 23-percent larger gain than Section B. The difference in gain is 2.17 with a probable error of 0.75. The critical ratio is 2.9, which means that the chances are more than 95 out of 100 that the gain made by Section A is actual and significant rather than a statistical error. We must consequently conclude that the gain exhibited in the post-test by Section A over Section B was due to the use of the study sheet.

Table IV shows the test results and the correlation coefficients between the pre- and post-

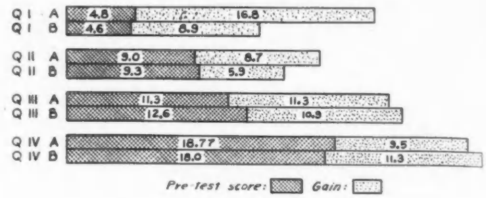


FIG. 1. Pre-test scores and gains: quartiles based on pre-scores.

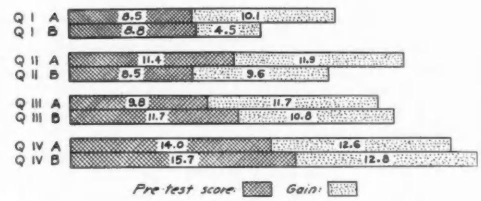


FIG. 2. Pre-test scores and gains: quartiles based on semester grades.

tests by quartiles based on the first semester grades. It is worthy of note that the correlation coefficients for all quartiles in Section B are large.

Table V shows the gains made when the quartiles are taken by two different methods indicated.

Figure 1 shows in diagram form the pre-test scores and gains by quartiles based on pre-test scores. Figure 2 gives the same type of information by quartiles based on semester grades.

Table VI presents data on the gains of the complete groups and a measure of the native abilities indicated by the semester grades.

In Table VII the two post-tests, fact and transfer, are compared. The section having the study sheet was 14 percent superior in gathering

TABLE V. *Gains.*

QUARTILES BASED ON PRE-TEST SCORES		QUARTILES BASED ON 1ST SEM. GRADES	
I, A	Gain 16.8	10.1	112 percent
I, B	8.9	4.5	51
II, A	8.7	11.9	100
II, B	5.9	9.6	111
III, A	11.3	11.7	120
III, B	10.9	10.8	92
IV, A	9.5	12.6	90
IV, B	11.3	12.8	81

facts and 2 percent superior in the ability to transfer and apply the fact to a new situation.

The *percentage learning* accorded an item is the percentage of those missing it on the pre-test who answered it correctly on the post-test. So defined, the percentage of learning is considerably too high, because, when a student misses an item, it is almost certain that the student did not know the correct answer, while the probability is that, for a five-answer multiple-choice item, one-fifth of the students who did not know the item *guess* it correctly. Statistically, then, the actual percentage learning, the percentage of those not knowing the item before seeing the film who have subsequently learned it, is less than the percentage credited to the item by the method used.

Consider a specific example. Suppose that of 100 students, 20 knew an item before they saw the film, and 80 did not know it. The number getting the item right on the pre-test was probably 36 and the number getting it wrong 64; that is, 20 of the 36 getting it right knew the item and probably 16 or one-fifth of those who did not know it, guessed correctly. Suppose now that the actual learning is 50 percent: of the 80 who did not know the item before seeing the film, 40 have learned it subsequently. After seeing the film, 60 know the item, but probably 8 of the remaining 40 guess it correctly on the post-test. However, according to the method used to get the percentage learning credited to the item, only the 64 who failed on the pre-test, from among the 80 who did not know, are considered. Of the 40 who have learned the item, probably 64/80ths, or 32, are among these 64, together with about 6 who do not know but guess it correctly, making a total of 38 rights among the 64. The percentage learning credited to the item is 38/64ths of 100 or 59 percent, whereas the actual learning was 50 percent. Thus all of the items are credited with more learning than they deserve; the smaller the learning, the greater the error.

TABLE VI. *Gain (whole test) vs. aptitude (1st. semester grades).*

	Section A		Section B	
	Gain	Grade	Gain	Grade
Average	11.36	5.50	9.33	5.54
S.D.	5.98	2.25	4.54	2.29
Correlation	+0.117	±0.092	+0.538	±0.063

TABLE VII. *Post-test fact vs. transfer.*

	Section A		Section B	
	Fact	Transfer	Fact	Transfer
Average	17.80	4.88	15.65	4.79
S.D.	5.1	2.8	5.4	3.7
Correlation	+.548	±.065	+.673	±.049

TABLE VIII. *A study of transfer item No. 3.*

	Number Successful on Number 3	Number Not Successful on Number 3	Success Ratio
No. getting 4 fact items, 8	8	0	∞
No. getting 3 fact items, 30	21	9	2.3
No. getting 2 fact items, 52	29	23	1.3
No. getting 1 fact item, 18	9	9	1

Each item was analyzed for the learning produced, and the results are summarized as follows:

Good learning (70–100 percent)

Solid and liquid metals and ionized gases are good electric conductors.

Non-ionized gases are not conductors.

Electric charge is the product of current and time.

Electricity exists as discrete charges.

The paths of electrons may be shown experimentally by using a ZnS screen.

Ag and H atoms are deposited in equal numbers by the same current.

The movement of charged oil drops is described by the Coulomb law of electrostatics.

The electron mass can be found from deflection experiments.

Poor learning (50–70 percent)

Metal ions are always found deposited on the negative electrode.

The mass deposited varies directly as the charge.

Ordinary air has few ions and is a poor conductor.

A charged electroscope is discharged when x-rays pass through the air around it.

Electrolytic conduction takes place in a liquid when the electrodes have ions between them and a potential difference.

Removing electrons from a body is equivalent to giving it a positive charge.

Potassium is photosensitive to light from an incandescent bulb.

Very poor learning (less than 50 percent)

The total mass deposited from an electrolyte is directly proportional to the atomic mass and inversely proportional to the atomic charge.

The electrons emitted by a hot filament go to the plate only when the plate is positive with respect to the filament.

Seeing the film produced either zero learning or confusion in the minds of the students with respect to the following three important items:

All the charge transported in any electrolytic solution is carried by particles charged + and −.

All electrons have the same charge regardless of their source.

In electrolytic conduction positive and negative ions move toward the cathode and anode, respectively.

The ability to transfer facts and principles to situations different from those in which the original learning occurred was investigated. The transfer examination was composed of 16 items. Facts used in these items were cast into situations differing from those in which the facts were presented in the film. Also facts needed for success on a transfer item were inventoried in the fact-finding examination. For example, transfer item No. 3 used facts that were inventoried in four of the fact-finding items. The 8 students who were successful on all 8 of the fact items were all successful on the transfer items. Of the 30 students who were successful on 3 of the fact items, 21 succeeded in the transfer item and 9 did not. Table VIII shows that the success ratio becomes smaller as the number of facts known becomes smaller. A study of this kind was made for each of the 16 transfer items, and the success ratios in practically every case descend in value as shown in Table VIII.

With respect to correlation coefficients, we should consider four points:

1. The correlation coefficients shown in Table III between the pre- and post-tests for Sections A and B were, respectively, 0.49 ± 0.07 and 0.77 ± 0.035. Both are surprisingly high. They indicate that there was much more shifting of positions in the test rankings in Section A than in Section B.

2. The absence of significant correlation coefficients for both sections for the *three low quartiles*, when based on the information possessed by the students, indicates a very wide spread of interchange of position within these quartiles. These coefficients are: I, $A=0.049\pm0.186$; II, $A=-0.056\pm0.18$; III, $A=-0.39\pm0.15$; IV, $A=0.69\pm0.09$; I, $B=+0.47\pm0.14$; II, $B=0.09\pm0.18$; III, $B=0.19\pm0.17$; IV, $B=0.74\pm0.08$.

3. When the quartiles are based on ability as shown by semester grades (Table IV) the correlation coefficients for all quartiles in Section A show much shifting of position within the quartiles. The correlation coefficients for Section B, however, indicate relatively little shifting of position within quartiles. The three sets of correlation coefficients give convincing evidence that the students in Section A did not make use of the aid given in the study sheet with effectiveness that correlates with ability or with information possessed as indicated by the pre-test scores. That is, *some students make better use of aid than others.* This appears to be true at every ability level. An indication of this same learning phenomenon without evidence so convincing was tentatively noted in the previous study made of the film "Electrodynamics."

4. From a consideration of the correlation coefficients for IV, A and B, in paragraph 2, the coefficients for IV in Table IV, and the gains made by IV in Table V and Figs. 1 and 2, three things are evident: (*a*) a considerable shifting of positions in the IV, A group; (*b*) A marked tendency to keep the same relative position in the IV, B group; (*c*) A gain in the upper B quartile equal to, or better than, the gain in the upper A quartile. This is true in spite of the fact that Section A had aid offered by the study sheet.

Some of the high A quartile were helped and others were retarded by the study sheet. The best students taken as groups did as well or better without aid as with aid. When there is so much confusion concerning the problem of teaching groups of different ability, this clear evidence seems particularly important.

Summary and Conclusions

(1) The technic previously set up for the evaluation of the teaching effectiveness of a sound motion picture film was improved and applied to the film "The Electron."

(2) Within the limits of the present experiment it has been shown that, using all ability quartiles as a group, the film is considerably more effective when a study sheet is used.

(3) The study sheet had its greatest effectiveness in the three lowest quartiles.

(4) The study sheet "slowed down" some of the best students.

(5) The conclusion, tentatively held in the study in the film "Electrodynamics," that some students show considerably more ability in making use of aid than others is substantiated in this study.

(6) The study sheet did not aid but probably hindered the best quartiles as a group.

(7) The teaching effectiveness of the film on the whole is high but it should be noted that the film had zero teaching effectiveness or created confusion on three important items.

(8) The more facts a student possesses concerning a principle, the more likely he is to apply the principle to a new situation.

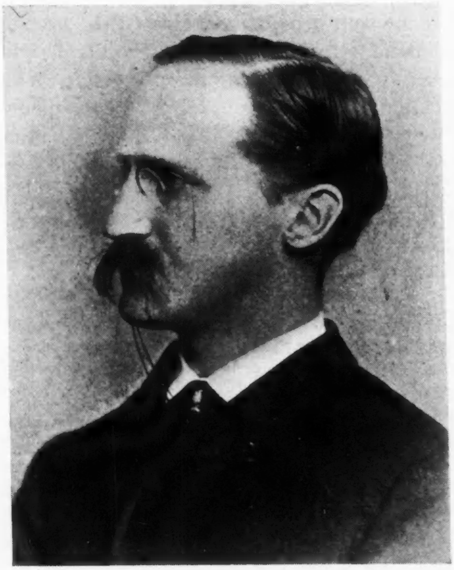
A Great American Physicist—Henry Augustus Rowland

Harry Fielding Reid
Johns Hopkins University, Baltimore, Maryland

HENRY AUGUSTUS ROWLAND was born at Honesville, Pennsylvania, on November 27, 1848. His father, grandfather, and great-grandfather were clergymen and graduates of Yale. When he was 11 years old his father died and he was left to the care of his mother and his two sisters. The bent of his mind was marked from childhood and took an undeviating and ever-strengthening course throughout his life. The following story is told of his boyhood. From the sheets of the family newspaper he made a hot-air balloon which, to the astonishment of his family and friends, made a triumphant ascent, landing, however, in a burst of flames on a neighbor's roof. The town's entire fire department rushed to the rescue and his boy friends begged him to hide, but he simply said, "No, I will go and see what damage I have done." No doubt the family told this tale with Washingtonian pride. Rowland's love of truth, however, was not so much a moral force as an intellectual necessity. Neither fear of punishment, nor any other thing, would have prevented him, young as he was, from discovering the error in his balloon. At the age of 16 his chemical experiments and glass-blowing led his family to think it the part of wisdom to send him to Phillips Academy at Andover, where he would be fitted for the academic course at Yale. He was miserable at Andover. Latin and Greek were abhorrent to him, and he wrote to the distressed and loving ladies at home, "Oh! take me home; it is simply horrible. I cannot get on here." Fortunately he was allowed to follow his own bent and he was transferred to the Rensselaer Polytechnic Institute at Troy, where, five years later, in 1870, he was graduated as a civil engineer.

After a year in railroad engineering, he obtained a professorship in Wooster College, in Ohio. The faculty decided that some instruction should be given in natural science, and, as Rowland was the youngest member of the faculty, the duty was forced upon him in spite of his insistence that he knew nothing of the subject. He was told to get the textbook and to keep a few lessons ahead of his class. Dissatisfied with its progress one day he asked the class if it could not advance more rapidly, and was answered by a voice in the rear, "We can, Professor, if you can!"

Rowland remained only a year at Wooster and then returned to the Rensselaer Institute, first as instructor in physics and then as Assistant Professor, a position he held until 1875. In spite of much routine work he continued his experiments. As early as 1870 he began work to determine the distribution of magnetism on iron and steel magnets, and soon found that little progress could be made without new experiments. At that time foreign physicists treated permeability as independent of the magnetizing force; but Rowland, by means of experiments performed with apparatus of his own making, showed conclusively that the permeability of iron and steel and nickel rise to a maximum and



Professor Henry A. Rowland.

then decline. He discovered the magnetic circuit and put the whole subject of magnetism on its feet. An examination of his work shows a thorough familiarity with the contemporary work of European physicists along this line, and a mastery of the necessary mathematics. His paper was sent to one after the other of the scientific journals of the time in America and was promptly turned down, evidently because the editors were unable to understand it. I doubt if there were a half-dozen persons in America who did. The physics taught in American colleges of that time was limited mainly to what today would be called undergraduate physics. But that condition, thanks mainly to Rowland, has been changed; all the important universities now give advanced instruction to graduate students. Rowland's profound knowledge of physics, however, came from his own experiments or from the foreign books that he could manage to buy or could induce the Institute to buy.

Rowland was sure of the value of his work on magnetism and when he failed to have it published in this country he was bold enough to send it to the great Maxwell, who was so much impressed by it that, as the Royal Society was not in session, he sent it to the *Philosophical Magazine* and personally corrected the proofs.

A little later, in 1875, the Johns Hopkins University was preparing to open its doors, and Mr. Gilman was reaching for competent persons to become the heads of the several departments. Once when talking to General Michic, then Professor of Physics at West Point, Mr. Gilman asked him if he knew of any suitable person to head the Department of Physics at the new university.

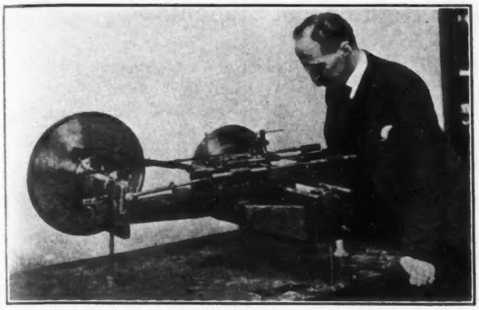
> He told me there was a young man in Troy, of whom probably I had not heard, whom he had met at the house of Professor Forsyth and who seemed to him full of promise.
>
> "What has he done?" I said.
>
> "He has lately published an article in the *Philosophical Magazine*," was his reply, "which shows great ability. If you want a young man you had better talk to him."
>
> "Why did he publish it in London," said I, "and not in the *American Journal?*"
>
> "Because it was turned down by the American editors," he said, "and the writer at once forwarded it to Professor Clerk Maxwell, who sent it to the English periodical."[1]

Mr. Gilman telegraphed to Rowland to come to West Point to see him. He was rather nonplussed to see so young a man—only 27 years old. Rowland told him of his work, of his desire to devote himself to physical investigations and of his correspondence with Maxwell. Mr. Gilman, about to go to Europe in the interest of the Hopkins, decided to take Rowland with him and let him select the scientific instruments which would be needed by the physical department.

Arrived at Cambridge, Mr. Gilman was more than pleased at the high praise the leading physicists there gave to Rowland's investigations. Here was just the type he wanted, a vigorous young man, who wanted only the opportunity to continue his researches, and who had already, at the age of 27, attained high standing with the leading physicists of the world. His professorship at the new university was assured. They soon separated, Mr. Gilman continuing his peregrinations in Europe and Rowland making for Berlin, to determine by experiment in Helmholtz' laboratory whether a moving quantity of static electricity would produce a magnetic field; that is, whether it would act like an electric current. The idea occurred to him in 1868 and is recorded in an old notebook of that date; but it was only now that the opportunity arose to carry out the experiment, and he promptly seized it. The famous Helmholtz put the resources of his laboratory at the disposal of Rowland, who worked so assiduously that the experiment was completed in a few months and gave definite evidence that a moving electric charge did give rise to a magnetic field. The principle of the experiment is simple, but the experiment itself required great skill to obtain definite and concordant results. Helmholtz was so impressed with Rowland's method and results that he presented an abstract of the experiment to the Royal Academy of Sciences of Berlin.

With the backing of such eminent physicists as Maxwell and Helmholtz, Rowland no longer had difficulty in publishing his researches in America.

[1] Fabian Franklin, *Life of Daniel Coit Gilman* (Dodd, Mead and Company, New York, 1910), p. 197.



Professor Rowland and his dividing engine.

The Johns Hopkins University opened its doors to students in the autumn of 1876, and Rowland entered on his duties as Professor of Physics. The times were propitious, the opportunity great and he was the right man to take advantage of them. From this time on he had the time and the means to carry on his great work. His duties were not onerous; indeed, he fixed them himself. He gave four lectures and held one journal meeting weekly. The latter was especially illuminating, for Rowland frankly criticized the papers reported on, and made clear where he thought they could and should be changed. His students took from him what they had in them to take. He did not suffer fools gladly. To those who could follow him, he was a great inspiration; for the others, it was a pure waste of time to attend his lectures.

When Rowland first went to Baltimore he immediately plunged into an elaborate determination of the Mechanical Equivalent of Heat which occupied his time for two or three years. His first paper on the concave grating was published in 1882. This was followed by paper after paper, each delving deeply into the mathematical theory of the concave grating, recording measurements of the relative and actual wavelengths of thousands of lines of the solar spectrum, producing the Photographic Map of the Normal Solar Spectrum, which has become standard the world over, and so forth. And between, and even during, his more elaborate investigations he published shorter articles on numerous physical subjects.

In looking over Rowland's *Physical Papers*[2] we are impressed by the meticulous care he gave to all details, and by the skill with which he handled his mathematics. He always emphasized the importance of theory and insisted that the value of an experiment depended upon the light it threw on theory.

He received many honors. He was elected to the National Academy of Sciences at the unprecedented early age of 33. He was made an honorary member of many foreign academies of sciences, received a number of medals and represented the United States in many international congresses.

He died on April 16, 1901 in his 53rd year, and was survived by his widow, Henrietta Harrison, two sons and a daughter. Of him Mr. Gilman said: "A great man has fallen in the ranks—great in talents, great in achievements, great in renown." No one could question this assertion.

Rowland's life was unique in its singleness of purpose. With genius at the helm it is not surprising that he reached the height of the great physicists in the realm of physical science. In America he was the pioneer from the trivial and commonplace to the eternal verities of physical science.[3]

[2] Collected by a committee of the Johns Hopkins University, and published by the Johns Hopkins Press (1902). An excellent commemorative address by T. C. Mendenhall appears in this volume and also in ***Biographical Memoirs***, Vol. 5 (National Academy of Science, 1905).

[3] For other biographical material on Rowland, see: H. B. Nason, ***Biographical records, officers and graduates, Rennselaer Polytechnic Institute*** (1887); *Who's Who in America*, vol. 1 (1899–1900); *The Sun* (Baltimore, Apr. 17, 1901); ***Nature*** (May 2, 1901); *Science* (May 3, 1901); H. F. Reid, Am. J. Sci. **11**, 459–462 (1901); J. S. Ames, Johns Hopkins Alumni Mag. (Jan., 1916); *Dictionary of American biography* (1935).

Much of the significance of accumulated knowledge lies in an understanding of the process by which it was accumulated.—JAMES BRYANT CONANT.

College Science Lectures to Honor High School Students

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A NEWSPAPER account of the first of these series of lectures five years ago began with a statement something like this: "If a breakfast food company gives away samples of its products, that's good business—but if a University gives away samples of its lectures, that's news."[1] And news it still is, for the University has just concluded its sixth series of orientation lectures, "The applications of the physical sciences," which are given on Saturday mornings to the 1000 highest ranking junior and senior high school students majoring in the sciences.

Very frequently the student in a high school science class is taught that particular science without being made aware of its many applications to industry or to other branches of science quite closely related, or to the well-being and happiness of humanity. These "Applications of the physical sciences" lectures, as the title suggests, did make an effort to correlate the various branches of the physical sciences. It was not physics for physics' sake, which certainly is important too, but it was physics as applied to chemistry, to aeronautical engineering, to mechanical engineering, to ceramics, etc.

The lectures this year were:

1. **The Physics of Air in Motion,** Samuel J. M. Allen, *Professor of Experimental Physics, College of Liberal Arts.*—Theoretical discussion of the principles involved in the motion of air past objects and of objects through air, showing the connection between pressure and velocity known as the Bernoulli and Venturi principles. Demonstrations of these relations: curving of golf balls, tennis balls and baseballs; hydrodynamic problems; light balls on air jets; airplanes and streamlining.

2. **Vibrations, Waves and Sounds,** Robert C. Gowdy, *Professor of Physics and Dean, College of Engineering and Commerce.*—Various kinds of vibrations were explained and illustrated by experiments, leading to a discussion of wave motion. Propagation, reflection and absorption of waves were demonstrated. The fundamental principles of vibrations and waves were applied to sound and to musical instruments.

3. **Clay and Clay Products,** Harold S. Nash, *Professor of Ceramics, School of Applied Arts.*—Formation of clays. Classification, preparation, shaping, firing and glazing of clay products. Chemistry of glasses and clays. Demonstrations of glaze-forming and pottery-firing. Lantern slides.

4. **Ancient and Modern Dyes,** Hoke S. Greene, *Associate Professor of Chemical Engineering, College of Engineering and Commerce.*—Discussion of the synthesis of natural dyes and many others not found in nature. Demonstrations of how dyes are made and used, what causes color in dyes and how color may be changed.

5. **Diesel Engines,** Reuel L. Smith, *Assistant Professor of Mechanical Engineering, College of Engineering and Commerce.*—Development of the Diesel engine; its place in modern industry and transportation; general characteristics of internal combustion engines and the unique characteristics of Diesel engines; economics of Diesel power. Many charts and lantern slides.

6. **Radiant Energy and Life,** Harold J. Kersten, *Assistant Professor of Mathematics, College of Engineering and Commerce.*—Discussion and demonstration of several forms of radiant energy, illustrating with lantern slides and exhibits some of the effects of one form of radiant energy (x-rays) on living things.

7. **Earthquakes,** John L. Rich, *Professor of Economic Geology, College of Engineering and Commerce.*—Description of earthquakes and their effects, followed by a brief discussion of means by which earthquakes are recorded and studied. The lecturer showed his pictures of the 1939 earthquake at Concepcion, Chile, which proved that damage, even in a severe earthquake, can be avoided by the right type of building construction.

Two such series of lectures are given in alternate years, so that a student who is high scholastically will be able to hear all 14 to 16 lectures in the last two years of his high school career.

At other times the topics were:

On Oxidation and Combustion, Henry M. Goettsch, *Professor of Inorganic Chemistry.*

Stroboscopy, the Science of Arresting High Speed Motion, Albert C. Herweh, *Instructor of Electrical Engineering.*

Sounds Made Visible, Laurence R. Culver, *Associate Professor of Electrical Engineering.*

Controlling Soil Erosions, John L. Rich, *Professor of Economic Geology.*

Visible and Invisible Light, Dare A. Wells, *Associate Professor of Physics.*

Nitrogen of the Air Made Valuable, Reuben S. Tour, *Professor of Chemical Engineering.*

From Soft Iron to Hardened Steel, Roy O. McDuffie, George M. Enos, *Associate Professors of Metallurgy.*

Building of the George Washington Bridge, Howard B. Luther, *Professor of Civil Engineering.*

[1] *Christian Science Monitor* **27,** No. 51 (Jan. 26, 1935).

What Makes It Fly, Bradley Jones, *Professor of Aeronautics.*

The Geologist's Share in the Finding of Oil, Walter H. Bucher, *Professor of Historical Geology.*

From Galileo to Einstein, Louis Brand, *Professor of Mathematics.*

The method of operation was relatively simple, once the plan was organized. Teachers of physics, chemistry, advanced mathematics and geology in all private, parochial and public high schools in the metropolitan area of Cincinnati were asked to select the students who were to be honored with invitations. In the past three years, the area has been widened to include all high schools within 25 mi of Cincinnati, consisting of corners of three states, Ohio, Indiana and Kentucky. The names of these teachers and the schools having been secured—a job in itself—the teachers were asked to mail printed cards indicating the name of the student and his address, the teacher's name, the science class, the number of students in the class and, equally important, the student's rank in that class. Only those students in the upper 10 percent of the class were to be given free tickets admitting them to the series of seven or eight demonstration lectures, all highly illustrated by actual experiments, or motion pictures or slides.

Because of the manner of selecting students and the fact that it was necessary for the student to show his ticket at the door for each talk, it was not surprising that about 80 percent of those invited attended most of the lectures.

There are several reasons why attendance has grown each year. The success of one year acts to boost interest the following year. Another factor is the closer cooperation between the high school teachers and the sponsor.

In the earlier years, some teachers, perhaps through distrust of the value or purpose of these lectures, or perhaps because of lack of interest, failed to return nomination cards. This meant, of course, that no one in the class had the privilege of hearing the talks. That seldom occurs now. Many teachers write in that they would like to recommend a boy or girl who just failed to make the top 10 percent, and who was interested seriously in science. Of course, such students are always admitted.

The first year that the lectures were given, many teachers asked whether they might secure an invitation for their own use. They were refused on the basis that it was wrong psychology to have students and their teachers together; some of the students might assume that the teachers were needed to maintain order. The second year, the requests for invitations by the teachers increased to such an extent that the lectures were given for them alone. Thus, during the first semester between Thanksgiving and Christmas, four double-header lectures were given from 9:30–11:30 A.M. on Saturday mornings. These were attended by 10 to 20 percent of the invited teachers. Now, since the student attendance at their own lectures is so large, and because a few adults from evening high schools attend, the presence of a few teachers who "sneak" into the student lectures is not considered objectionable.

The first time this scheme was reported as "A novel experiment,"[2] the following statements were made:

> Obviously, the inauguration of a program on such scale involved a great deal of organization and work. To see these alert young men and women appearing almost an hour before the lecture in order to secure choice seats, to notice how they paid strict attention for 60 to 70 min during the lecture, to view them inspecting carefully all the apparatus on display and to watch them go through the various laboratories of the university after the talks certainly compensated for whatever work was involved on the part of the faculty.
>
> What the students gained from these lectures is quite obvious. They got a preview of university lectures and university laboratories. They learned what the various sciences are like and how they are interrelated. They found out that the stadium wasn't the only place on the campus, and especially pleased were they when they realized that their intelligence was respected and rewarded.
>
> Of course, the university benefited too, because it fulfilled another obligation to its taxpayers. It has now made contact with one more group of its citizens. It caters, as any university should, to the people of college age by its day classes; to those who have to work in the day time by its evening classes; to those who stay at home by its radio lectures; and now to those students approaching college age by these series of inspirational and valuable talks.

These statements still hold true.

[2] Sch. and Soc. **44**, 13–14 (1936); digested in Am. J. Phys. (Am. Phys. T.) **5**, 96 (1937). A second report of progress appeared in J. Eng. Ed. **29**, 479–482 (1939).

NOTES AND DISCUSSION

A Circular Periodic Chart

The periodic chart of elements originally proposed by Mendeléeff is based on the arrangement of elements in order of increasing atomic weight. It is well known that, according to this chart, elements that are chemically alike arrange themselves into certain groups. After the discovery of the significance of the atomic number as representing either the number of units of positive charge on the nucleus of the atom or the number of extranuclear electrons in the neutral atom, the "order number" in the periodic chart has come into greater prominence. It has not, however, been possible to indicate in the chart the rare earth elements, and this difficulty has now been traced to the fact that in these elements the $4f$ subshell is being filled up by electrons. Such characteristic features of an atom as its valency, its spectroscopic ground term, its chemical and physical properties owe their origin to the way in which the electrons are distributed around the nucleus in the various shells and subshells.

A new periodic chart (Fig. 1) has been devised with a view to bring into prominence this significant distribution of the electrons in the various shells. Except for a few elements, which are shown bracketed, the electron distribution in various shells and subshells of an atom of atomic number Z is obtained by considering that one electron exists in each place marked from 1 to Z, inclusive. This arrangement naturally leads to all the periodic properties usually found in the classical chart and, in addition, gives a simple method of denoting the atom building by electrons. After La^{57} the f subshell of the N shell gets continuously filled up, and after 14 electrons are put in we have Lu^{71}, the last of the rare earth elements; next the $5d$ orbit gets filled up, and we continue the chart with Hf^{72}. In the case of about a dozen elements, shown inside brackets, the electron distribution is slightly different from that indicated in the diagram. For instance, in the cases of Cu^{29}, Ag^{47} and Au^{79}, the chart shows the electron distribution as d^9s^2, while as a matter of fact the distribution is $d^{10}s^1$, in consequence of

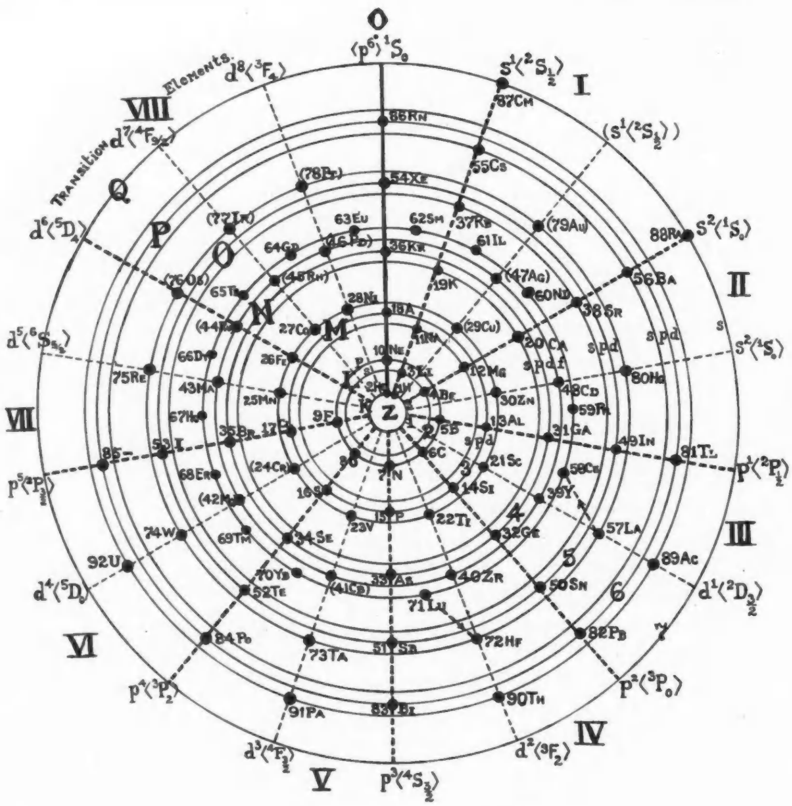

FIG. 1. A circular periodic chart that indicates the electron distribution in atoms.

which they form the first subgroup. The electron configuration of the ground state and the corresponding spectroscopic term are indicated in the chart. This chart brings out essentially the electron distribution in atoms, while retaining all the advantages of the Mendeléeff chart.

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Dowmetal Tubing for Archimedes' Principle Experiments

ONE of the corollaries of Archimedes' principle is that a floating body displaces a weight of the liquid equal to its own weight. When the liquid is water this means that the weight of the body, expressed in grams weight, is very nearly equal numerically to the volume immersed, expressed in cubic centimeters.

To illustrate this principle in the elementary laboratory at Brown University, a long, graduated cylindrical tube, loaded with fine lead shot, is weighed, and then the volume immersed when floating is measured. More shot is then added and the new weight and volume are compared, etc.

The chief difficulty with this experiment is that any ordinary tube will not float stably until it is almost completely immersed, which greatly reduces the number of possible readings and the accuracy of the experiment. The smaller the density of the material and the thinner the walls, the larger the fraction of the tube which protrudes when stability is attained by adding lead shot. Heretofore, thin-walled, graduated glass cylinders have been used with good results, except for frequent breakage, especially when pouring the shot. On this latter account, glass had to be abandoned in favor of something less fragile. Most metals are so dense that the walls would have to be extremely thin, but Dowmetal, a magnesium alloy of specific gravity 1.7, has proved very satisfactory. A tube of outside diameter 1 in., length 20 in., and wall thickness $\frac{1}{16}$ in., with a plug which screws into the end,[1] will float stably with more than 15 cm of the tube out of water when a moderate amount of shot has been added. Thus, approximately one-third of its length is available for measurements. Fifteen circular marks, 1 cm apart, are cut around the tube with a lathe. Finer graduations are not necessary because the length immersed can easily be controlled by exercising care in adding the shot.

Probably some plastics might serve the purpose but these have not been tried since the Dowmetal has proved so satisfactory.[2] Certainly no other *metal* adequately fulfills the requirements.

This tube can also be used in a simple hydrometer experiment for liquids both denser and less dense than water.

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[1] These tubes may be obtained from the Dow Chemical Co., Midland, Mich. at a cost of 26 cts./ft plus shipping.

[2] A thin oil or vaseline film on the tube overcame its slight tendency to corrode in Providence city water.

A Simple Torque Apparatus

THE problem of the equilibrium of nonconcurrent forces is relatively difficult for students to visualize, and some sort of laboratory experiment is desirable to clarify the subject. Several good pieces of apparatus have been developed for the purpose, such as the University of California moment apparatus and the Hall composition of force board. The chief objections to their use are that considerable friction is involved, numerous parts are required and, in the complications of setting up the problem, the theoretical implications may be obscured.

The apparatus which we have developed for this purpose is simple in the extreme, has few parts and is easy to use. It consists of a 7.5-cm square of 20-gauge aluminum (Fig. 1) in the border of which several holes have been

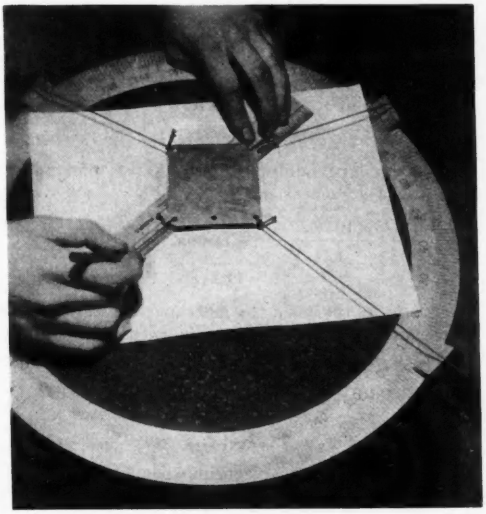

FIG. 1. A simple torque apparatus.

drilled. In these holes as many cords as desired may be attached by means of snaps such as are used by fishermen on leaders. The whole system is placed on an ordinary horizontal force table, above which it "floats" because of the lightness of the aluminum. The student places a sheet of paper on the table, draws lines directly under the cords and then, using protractor and ruler, calculates the vector sum of the forces and the sum of their torques about each of *two* points situated anywhere on the paper. Two points are used to strengthen the idea that when a body is in equilibrium the total torque about *any* point is zero. The accuracy of the results depends mainly on the sharpness of the pencil used in drawing the lines.

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A Derivation of the Mechanical Equivalent of Heat from the Kinetic Theory of Gases

THE molar thermal capacity of a monatomic gas at constant volume, C, is 2.98 cal mole^{-1} deg^{-1}, as determined experimentally. The kinetic theory may be employed as follows to provide an expression for this same energy change in mechanical units. This mechanical expression may then be equated to C to yield the mechanical equivalent of heat.

The fundamental equation of the kinetic theory, $pv=\frac{1}{3}nmu^2$, may be solved for the root-mean-square molecular velocity u; thus, $u=(3pv/nm)^{\frac{1}{2}}$. In the case of 1 mole of monatomic gas, if M is the molecular weight, $u=(3pv/M)^{\frac{1}{2}}$.

Consider 1 mole of gas at 0°C and again at 1°C with pressures p_0 and p_1 and with molecular velocities u_0 and u_1, respectively; then,

$$u_0^2=3p_0v/M,$$
$$u_1^2=3p_1v/M=3(274/273)p_0v/M.$$

Therefore, the difference of the kinetic energies of 1 mole in the two different states is given by

$$\Delta E=\tfrac{1}{2}M(u_1^2-u_0^2)=\tfrac{1}{2}M\cdot 3p_0v/M(274/273-1)=p_0v/182.$$

Under standard conditions p_0 is 1.01325×10^6 dyne cm^{-2}, and v is 22,414.1 cm^3. Hence,

$$\Delta E=\frac{1.01325\times 10^6\times 22{,}414.1}{182}\text{ erg mole}^{-1}\text{ deg}^{-1}$$
$$=12.4786\times 10^7\text{ erg mole}^{-1}\text{ deg}^{-1}.$$

This value of the molar thermal capacity of a monatomic gas at constant volume expressed in mechanical units may be equated to C, or 2.98 calories; thus

$$12.4786\times 10^7\text{ erg mole}^{-1}\text{ deg}^{-1}=2.98\text{ cal mole}^{-1}\text{ deg}^{-1},$$

or

$$4.19j=1\text{ cal}.$$

The value of the mechanical equivalent of heat obtained in this way is in good agreement with experimentally determined values.

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"Stripped Problems" Tests

MANY teachers frequently give 5- to 15-minute written quizzes or tests at the beginning of class periods. Often these consist of only two or three questions or problems. It is suggested here that *for some purposes* tests consisting of four or five times as many "stripped problems," and administered in the same amount of time, are superior to those of the more conventional type.

"Stripped problems" are problems which, divested of nearly all mathematics, stand bare physically. To comprehend their meaning and achieve their solution requires physical thinking almost exclusively. They deal with simple and elementary concrete situations. Hence the time and thought required for the visualization of the physical pictures presented by the problems and for computation are reduced to a minimum. This gives relatively more time for those thought processes involved in the application of fundamental principles and concepts to particular physical situations.

The following is a typical test made up of such problems.

1. An object of mass 1 g, referred to hereafter as M, rests on a horizontal frictionless plane. A force of 1 dyne, referred to hereafter as F, acts horizontally upon M. Find the acceleration of M.

2. The object M lies on a table that exerts a frictional force of 1 dyne upon M when it slides. Find the acceleration of M when F acts on it horizontally.

3. The object M moves on a table exerting a frictional force of 1 dyne upon it. To give M an acceleration of 1 cm/sec^2, how large a horizontal force must be applied to it?

4. An object on a frictionless table has an acceleration of 2 cm/sec^2. The horizontal force upon it is 1 dyne. Find the mass of the object.

5. The force F is applied vertically upward upon M at a point above the earth's surface where the acceleration due to gravity is 1 cm/sec^2. Find the acceleration of M.

6. The force F is applied vertically downward upon M in a region where the gravitational acceleration is 1 cm/sec^2. Find the resultant acceleration of M.

7. The force F acts upward upon a body in a region where the gravitational acceleration is 1 cm/sec^2. The resulting acceleration is $\frac{1}{2}$ cm/sec^2. Find the mass of the body.

8. The force F acts upward upon M in a region where the gravitational acceleration is 980 cm/sec^2. Find its acceleration, both in magnitude and direction.

9. At a point where the gravitational acceleration equals 1 cm/sec^2 a thread can support M while at rest without breaking, but no more. (Such a thread is hereafter called T.) Find the minimum number of such threads needed to form a cable capable of lifting M with an acceleration of 1 cm/sec^2 upward at a place where g is 980 cm/sec^2.

10. A thread T hung over a pulley has an object attached to each end. If the masses of the objects are equal, how large may they be if the string is not to break, in a region where the gravitational acceleration is 1 cm/sec^2.

11. An unbreakable cord of negligible mass is hung over a pulley which is frictionless and has no inertia. A body of mass 1 g is hung from one end, one of mass 2 g is hung from the other end. Find the acceleration of each body in a region where the gravitational acceleration is 1 cm/sec^2.

12. In problem 11 what will be the force in the cord?

Obviously there are many other permutations and combinations of the primary concepts involved here. It would be valuable exercise for the student, after thorough discussion of the foregoing problems, to transmute them into a new set in which F is, say, 1 g, everything else remaining equal. Occasionally, too, an exceptional student will accept the challenge implied by making $M=1$ kg and $F=1$ poundal.

Such tests have the following advantages among others:

(*a*) They are objective and of great diagnostic value. Since each problem is simple, definitely delimited, and

specific in its conceptual content, a set of them dealing with a group of primary concepts provides a highly effective discriminatory probe with which to isolate for the student his misunderstandings or errors in method—and for the teacher, perhaps, unsuspected weak spots in his teaching.

(*b*) Many students ascribe their difficulties to poor training or lack of ability in mathematics. While often this is altogether too true, the real difficulty frequently lies deeper—in the physics itself. Tests such as this one identify that particular malady rather convincingly.

(*c*) Such a test assays the student's mastery of a field more widely than does one of equal length involving fewer problems and more complicated situations because it contacts a particular subject at more points.

(*d*) The student is encouraged to emphasize fundamentals in his daily study. Many students work superficially; they have the evil habit of attempting to solve assigned textbook problems before thorough study of underlying principles. For such students it is a disconcerting and highly revealing experience to be confronted by a "stripped problems" test; it "calls their bluff."

(*e*) The problems are exceptionally useful in the study of units.

(*f*) After such a test a class is always ready with questions which go to the very heart of a subject. It would be difficult to find a more effective method of raising such questions in the students' minds and of bringing the student to active participation in the explorations of basic concepts and laws.

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An Experiment on Acceleration

OF all the experiments performed in the introductory course, perhaps none is more fundamental in character and at the same time more difficult to design than the experiment on motion with constant linear acceleration. All the methods available for performing the experiment, save one, involve a correction for the inevitable friction, if the relation $F=ma$ is to be illustrated; and this, just as inevitably, seems to the student to be an arbitrary procedure necessary to make the experiment come out "right."

The exception mentioned is that of a freely falling body. Air resistance may be ignored when the experiment is performed under the usual laboratory conditions. In this case the acceleration is so large that some method of accurately measuring small time intervals must be provided. Many methods have been proposed and used, varying from the electric spark to periodic squirts of ink. The former is a good example of complications which may be confusing to the beginner, and the latter illustrates a common type of untidiness which is not altogether desirable.

The Whiting pendulum,[1] on the other hand, possesses none of these disadvantages. It is simple in principle and practice, dependable, accurate, and does not require careful preliminary adjustment by the instructor. As used in the past, however, it has been a rather inflexible instrument which allowed one to measure the acceleration due to gravity but did not forcibly illustrate the distance of fall as a function of time. A variable pendulum period and, therefore, various times of fall may obviously be obtained by varying the length of the pendulum.

Now, if the pendulum is a simple one, a short calculation shows that, for collision to occur, the distance S which the ball falls is related to the length l of the pendulum by the relation $S=\pi^2 l/8$. So, if the pendulum is constructed to approximate a simple one, the point of release of the falling body is always above the point of suspension of the pendulum, a fact that greatly simplifies the design of the apparatus.

A rather complete drawing of the apparatus is given (Fig. 1), together with the instructions that have been worked out by trial and error. A piece of $\frac{3}{4}$-in. square iron stock D is fastened vertically about 1 in. from the wall and between floor and ceiling. Three clamps as illustrated are made so that they may be fastened at any convenient position on the rod by tightening the thumbscrews. From

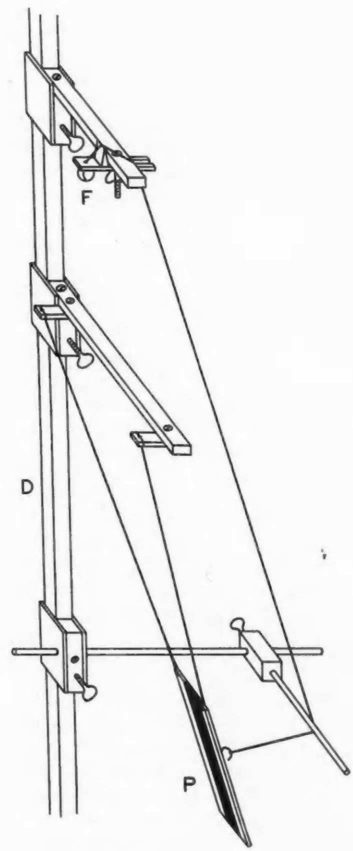

FIG. 1. Modified Whiting pendulum for the determination of distance of free fall as a function of time of fall.

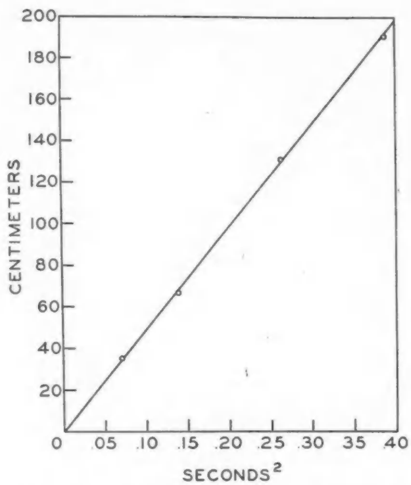

FIG. 2. Plot of S *vs.* t^2, from data obtained by a student during a regular laboratory period.

these the supports for the falling body, the pendulum and the holding rod are fastened. The pendulum bob P is made of $\frac{1}{4}$-in. iron, 2×8 in., and is suspended from two holes in its upper corners. The falling body F is a solid brass sphere about 1 cm in diameter,[2] with a fine slot (0.010 in.) cut to its center. String may be quickly and securely fastened by wrapping it twice through the slot. A ridge is provided so that the string may be easily cut with scissors near the point of support.

Following is the procedure and a result which is quite typical of those obtained by first-year students:

Suspend the pendulum plate by two strings so that the distance from its center to its support bar is about 50 cm (not critical). Pass the plumb bob thread through the hole in the upper supporting rod and adjust the upper support until the plumb bob just touches the front of the pendulum plate at its center. This assures that the ball will hit the pendulum at the lowest position of the pendulum. Now arrange the ball and pendulum as shown in Fig. 1. Wait until the pendulum has become motionless and then cut the thread near the top. If the ball misses the plate, raise or lower the upper support and repeat until the ball and pendulum collide. For each trial be sure to adjust the plumb bob as previously described.

Fasten a piece of sensitive paper[2] on the face of the pendulum plate with Tacki-wax,[2] and note where the ball hits. Raise or lower the upper support an appropriate distance so that the collision occurs near the center of the pendulum plate. Measure the distance of fall from the center of the ball at its upper position to the point of collision with the pendulum. Repeat this determination twice. (If a number is placed alongside each hit, the various hits will not be confused.)

Now pull the pendulum plate back to a somewhat greater angle, cut the thread near the *plate* and find the time for 10 complete vibrations. One-quarter the period is the time of fall of the ball. Repeat this whole procedure for pendulum lengths of 25, 100 and 150 cm, and if there is time, for as great a length as possible.

Plot the distance of fall as a function of the square of the time and draw the best straight line through the points, including the origin (Fig. 2). Find the slope of the curve and from this compute the acceleration g, expressed in ordinary units.

From the graph, read off the position of the falling body at successive intervals of 0.05 sec from the starting time. Obtain the first and second differences,[3] the average of the second differences, and from this again calculate the value of g.

The value of g from the slope of the curve (Fig. 2) is 974 cm/sec^2, giving an error of 0.61 percent, and that calculated from second differences is 972 cm/sec^2, giving an error of 0.81 percent. Of course, somewhat more exact results may be obtained by a more experienced experimenter.

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[1] See, for example, Sutton, ed., *Demonstration experiments in physics* (1938), Exp. M-86.
[2] Central Scientific Company.
[3] See for example, Knowlton, *Physics for college students* (McGraw-Hill, 1928), p. 158.

An Electronic Voltage Regulator for a Small Direct-Current Generator

FOR most laboratory purposes, the source of direct-current supply must be of constant voltage. A motor-generator set using a flat-compounded generator and directly connected to a synchronous motor supplied from constant frequency mains is a satisfactory means of supplying such a constant direct-current source. With an induction motor for the drive, the direct-current voltage may be made essentially constant by sufficient over-compounding to compensate for the slip of the motor. On the other hand, if the frequency of the supply system is not constant, the voltage output of the generator will vary with it, even though the load on the motor-generator set remains unchanged.

The direct-current generator in this laboratory is of 4-kw capacity, is approximately flat-compounded and is driven by a directly connected 5-hp induction motor operating from the 220-v, 3-phase, 60 cycles/sec mains. The power supply is from the college generators, and, since the capacity of the system is relatively small and the engine governors somewhat sluggish, the frequency regulation is not good. At times the frequency variation causes voltage fluctuations in the d.c. generator of 20 percent or more with no change of load on this generator.

This difficulty has been completely corrected by the addition of an electronic voltage regulator[1] which holds the voltage constant to within $\frac{1}{2}$ percent regardless of load or frequency variations.

Figure 1 is a diagram of the circuit giving some of the constants. The power supply is from the same source that

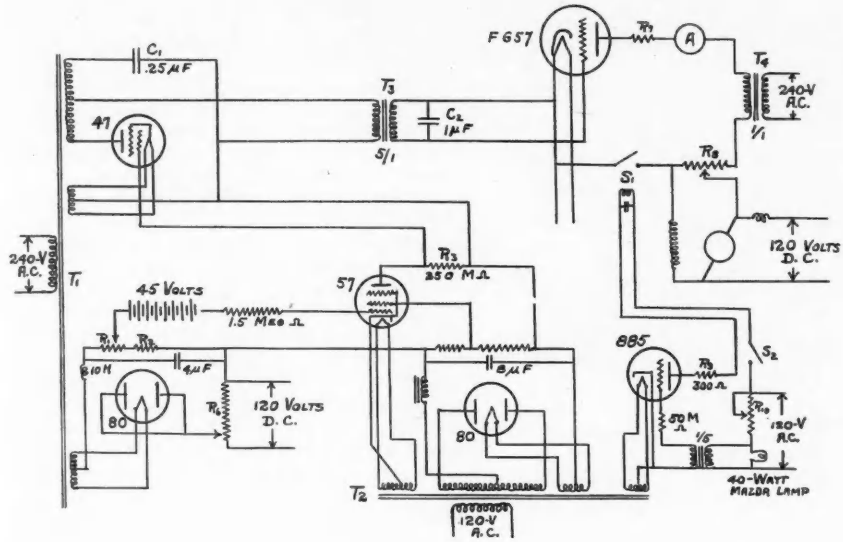

FIG. 1. Wiring diagram.

is used for operating the generator-driving motor. The cost of the parts used in the regulator, including the special transformer T_1, is about $50.

Only one tube is used in the final stage—a grid-controlled rectifier or "Thyratron," General Electric type FG57. The unidirectional and pulsating current from this tube is applied directly across the shunt field rheostat of the generator in the opposite direction to the normal generator field current. This is equivalent to a reduction of rheostat resistances which causes the generator field current to be increased. The regulator output is constantly and momentarily changed in proportion to the indications of the voltage-sensitive element, and so the generator field current is constantly regulated to the point that will make the generator voltage constant.

The resistor R_7 and rheostat R_8 should be sufficient to limit the current to the safe maximum value for the tube. The transformer T_4 serves solely to isolate the line voltage from the generator. The heater current for the FG57 is supplied from a winding on the transformer T_1.

The Thyratron output is controlled by means of a phase-shifting circuit using the 47 tube. The constants, obtained by a cut-and-try method with the help of a cathode-ray oscillograph, give a satisfactory range of operation. The 47 tube acts as a controlled resistance operated from the output of the amplifier. The grid transformer T_3 should be a heavy duty audio-type transformer, preferably one wound with about No. 36 enameled wire.

In order to drive the Thyratron tube over the range necessary for full load regulation, it is necessary to amplify the signal voltage. This is done by means of the single-stage amplifier using the 57 tube. The circuit is a conventional one, consisting of this tube with an associated power supply which should be well filtered.

The voltage-sensitive element of the circuit is a type 80 tube with the plates tied together. The filament is heated to normal operating temperature by means of a filament winding on the transformer T_1. The plate supply for this tube is a potentiometer rheostat which is connected across the generator that is being regulated. Any variation in voltage of the generator causes a corresponding change in the plate current, and this in turn changes the voltage across the resistance R_1R_2, which consists of a 2200-ohm resistor in series with a 400-ohm potentiometer. This potentiometer permits changes of generator voltage to be made, the range being approximately ± 25 percent of normal voltage. The 45-v B battery is connected as shown so that the difference-voltage is applied directly to the grid of the type 57 amplifier tube. Since the operating point of the 57 requires a negative grid, the battery does not deliver any current; it serves only as a standard of potential and therefore its useful life should be equal to its shelf life. The type 885 tube is not necessary in the regulation of a generator. Its use will be discussed later.

The regulator is placed in operation by first warming up the filaments, and then closing the switch S_1. As soon as the voltage falls below the point for which R_1 is set, the current will start in the regulator output circuit, thus maintaining the voltage. In practice it is well to leave R_8 set at a point that would supply only 90 to 100 v on the generator; the regulator will then continue to work and hold the voltage constant, even if the speed of the motor should become considerably larger than normal. The operating point may be set, by means of R_1, to any desired terminal voltage of the generator.

Figure 2, obtained by recording the variations of voltage on strips of motion picture film, shows some of the results obtained with and without the regulator. The uppermost curve, obtained without the regulator in operation, shows

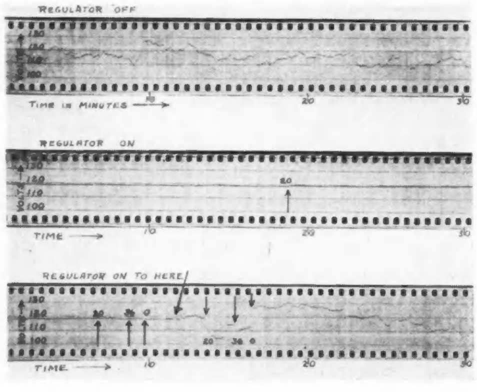

FIG. 2. Graphs showing regulator action.

the voltage variations that occur when there is no change of generator load; the voltage fluctuates continuously as well as drifts in a downward direction. The second curve, obtained with the regular in operation, shows the voltage maintained at a very steady value of about 118 v. At the time indicated by the arrow, a load of 20 amp was suddenly switched onto the generator. This is more than half of the generator capacity, but with the regulator in operation there is scarcely a ripple in the voltage graph. The third curve shows how well the regulator performs. The loads were made 20 amp, then 36 amp, which is more than full load for the generator, and finally zero load. The regulator was then taken off and the same cycle of load change repeated on the unregulated generator. The resulting erratic curve shows just how effective the regulator is in stabilizing the voltage.

The operation of this regulator closely resembles that of the well-known Tirrill regulator, which is often used for voltage control of alternators; and it is possible to employ it for alternator voltage regulation by using, instead of the d.c. plate supply from the potentiometer R_6, an a.c. plate supply to the voltage sensitive type 80 tube. This a.c. voltage is taken from a winding of about 200 v on the secondary of the transformer T_1. The type 80 tube is arranged for double wave rectification, and the output is well filtered before passing through the resistors R_1R_2. The regulator is then sensitive to voltage variations of the a.c. supply, and if the regulator output is applied to the shunt field rheostat of the exciter, the alternator voltage will be regulated. The output and range are sufficient to control up to 6- or 8-kw capacity.

We have used the equipment here described for the regulation of three different alternators, and have found it comparable in performance with the Tirrill regulator. However, it is necessary to apply an anti-hunting circuit[2] to make the apparatus useful for alternator regulation. It would also be advantageous to supply an overvoltage relay to the system in case of tube failure or other defect causing the voltage to rise. An electronic relay which is satisfactory for this purpose is incorporated in the circuit of Fig. 1. In this arrangement the switch S_1 is replaced by a small relay which is operated by the rectified output from the type 885 tube. The relay circuit is adjusted so that the current from the 885 will be cut off as soon as the voltage across the 40-w Mazda lamp rises to some predetermined value. This operating point may be set by changing the value of the resistor R_{10}.

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[1] F. H. Gulliksen, Elec. Eng., June, 1934, p. 877; Aug. 1936, p. 873.
[2] Anti-hunting circuits are described by Gulliksen and Vedder, *Industrial electronics*, p. 184.

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- R. T. Birge, *The Propagation of Errors*, 30 cts. for 6 copies.
- J. C. Hubbard, *Ultrasonics*, 50 cts. for 6 copies.
- W. H. Michener, *A Brief Table of Meter-Kilogram-Second Units*, 15 cts. for 6 copies.
- R. P. Johnson, *Solid Fluorescent Materials*, 40 cts. for 6 copies.
- L. A. DuBridge, *Some Aspects of the Electron Theory of Solids*, 35 cts. for 6 copies.
- D. E. Wooldridge, *The Separation of Isotopes*, 40 cts. for 6 copies.
- M. Randall, *Electrolytic Cells*, 60 cts. for 6 copies.
- J. C. Stearns and D. K. Froman, *Cosmic Rays—Their History, Source, Nature and Effects*, 60 cts. for 6 copies.
- C. W. Ufford, *Spectroscopy—A Survey*, 45 cts. for 6 copies.
- A. A. P. T. Committee, *Proposal to Standardize Letter Symbols*, 50 cts. for 6 copies.
- A. A. P. T. Committee, *Suggested Four-Year Curriculum Leading to a Major in Physics*, 5 cts. per copy.
- A. P. S. Committee, *Physics in Relation to Medicine* (1923), 10 cts. per copy.
- A. A. P. T. Committee, *Teaching of Physics for Premedical Students* (1937), 15 cts. for 6 copies.
- P. W. Bridgman, *Society and the Intelligent Physicist*, 10 cts. per copy.

Graduate Appointments Available

Virginia Polytechnic Institute, Blacksburg, Va. *Fellows*, **$400**; *assistants*, **$300**. For a list of appointments available in other institutions, see the February, 1941, issue, page 53.

RECENT PUBLICATIONS AND TEACHING AIDS

General Physics

Physics. Philo F. Hammond, Professor of Physics, University of Wyoming. Ed. 2. 770 p., 824 figs., 15×23 cm. *Mountain States Pub. Co.*, $4.75. The first edition of this textbook for science and engineering students has been in use since 1932, but only in the author's institution. The main branches of elementary physics are treated in the usual order, with most of the modern physics appearing in a 64-page section at the end. The whole treatment is rather extensive, and includes material that will serve to make the book useful also for reference purposes in later courses, especially in engineering. The author points out that he has devoted little space to the purpose of "extolling the wonders of physics," since he believes that a thorough knowledge of a subject is essential to an interest in it and that an appreciation of the subject follows when the course is well taught. The textbook is also available in a two-volume edition, priced at $2.60 per volume, with the first volume containing only mechanics, heat and sound.

Fundamentals of College Physics. Willibald Weniger, Professor of Physics, Oregon State College. 702 p., 340 figs., 29 tables, 15×23 cm. *American Book Co.*, $3.75. In this textbook for a standard, general course, the author has emphasized classical physics in the belief that "If a decade ago it required a year for the student to master the fundamantals then recognized, it probably will take a year to do so now." The arrangement of the main divisions of the book also is traditional; but the whole treatment has been unified by developing it about *motion* as a central theme—the motions of rigid bodies, molecular motions, motions in mediums and motions of electric charges. There are 58 brief chapters, a few of which are devoted to summaries of preceding groups of chapters, or to restricted topics such as the physical equation, the gyroscope and refrigeration. The explanations are terse rather than voluminous, for the author is convinced that most students prefer this type of treatment. The formulas generally are developed in the text, although several are merely stated and interpreted, on the ground that long and tedious methods designed to avoid the calculus are usually not worthwhile. Numerous illustrative problems are solved in detail in the text proper.

Classical and Modern Physics. Harvey E. White, Associate Professor of Physics, University of California. 720 p., many illustrations, 15×23 cm. *Van Nostrand*, $3.75. Every teacher who is concerned with the development of an introductory, cultural course in physics should examine this textbook, which represents a thoroughly planned and apparently successful attempt to bring together in a single volume an elementary presentation of classical physics and a relatively comprehensive survey of modern physics. The modern physics occupies 239 pages, or 16 chapters out of a total of 43, and deals, more or less in the order of their historical development, with electrons, atoms and the periodic table, x-rays, radioactivity, the spectrum, classification of spectra, photoelectricity, structure of the atom, photon collisions and atomic waves, cosmic rays, atomic collisions and nuclear disintegrations, induced radioactivity, the nucleus, and certain aspects of astrophysics. The discussions of these topics are clear, simple and quite comprehensive; for example, the chapter on atomic structure deals briefly with Rutherford's scattering experiments, Bohr's electron-jumps, normal and excited atoms, Bohr's newly predicted series, the Bohr-Stoner scheme of the building up of atoms, the sodium atom, ionized atoms, the spinning electron, origin of x-rays, and origin of band spectra. The illustrations are exceptionally well chosen and are really useful. Lists of questions and simple problems with answers accompany each chapter.

Physics for Premedical Students

Radiology Physics. John Kellock Robertson, Professor of Physics, Queen's University (Canada). 285 p., 188 figs., 33 tables, 15×23 cm. *Van Nostrand*, $3.50. Recognizing that it is almost impossible to teach in one year the fundamental principles of physics, and at the same time to deal adequately with those applications with which a medical student should be familiar, Queen's University has instituted a two-year course in physics for premedical students, with the first year devoted to the usual elementary work in mechanics, heat, sound and light, and the second year given to lectures and laboratory work in electricity and magnetism that lead naturally to a consideration of such subjects as x-rays, radioactivity and nuclear physics. The present textbook, which covers, with some amplification, the work which the author has been giving in the last half of the second year, provides a systematic treatment of the basic physical principles used in the field of radiology. Although the author assumes that the reader has had a course in general physics, he frequently reviews and amplifies important elementary topics. Thus the first chapter begins with a review of essential electrical principles and then proceeds to a treatment of alternating currents. The remaining 15 chapters deal, in turn, with the production, measurement and control of high voltage, cathode rays, positive rays and isotopes, x-ray tubes, valve rectification, properties of x-rays, electromagnetic waves, measurement of x-ray wave-lengths, secondary x-rays and absorption, x-ray dosage, radioactivity, supervoltage tubes and high speed particles, artificial radioactivity, and high frequency currents. A list of 132 questions and problems are included in the appendix. Since this book in combination with existing general physics textbooks immediately provides the basis for an integrated

three- or four-semester course for premedical students, its publication should prove to be of great interest to all who agree with the premedical committee of the American Association of Physics Teachers in its contention that the physics prerequisite should exceed one year [Am. J. Phys. **5**, 267 (1937)]. Certainly every undergraduate student who is interested in medicine or biophysics should have access to the book, and it can also be recommended to radiologists and technicians who desire relatively simple explanations of the physical principles underlying the use of their apparatus.

Advanced Physics and Mathematics

Storage Batteries. George Wood Vinal, Physicist, National Bureau of Standards. Ed. 3. 474 p., 170 figs., 60 tables, 15×23 cm. *Wiley*, $5. A comprehensive survey of the physical and chemical facts and theories about batteries, of charging methods and equipment, of maintenance and testing methods, and present-day uses for batteries is provided by this book. In the present edition, obsolete and less important subject matter appearing in the 1924 and 1930 editions has been deleted to provide space for recent advances in theory and applications without increasing unduly the size of the book. About half of the illustrations are new. As before, emphasis is laid on the scientific principles involved, but the treatment has not been allowed to become so technical as to restrict its usefulness.

Introduction to Algebraic Theories. A. Adrian Albert, Associate Professor of Mathematics, University of Chicago. 145 p., 17×23 cm. *University of Chicago Press*, $1.75. This textbook is intended for a new, third course in college algebra that will bridge the gap in mode of thought between the intuitive treatment of the usual first course in the theory of equations and the rigorous abstract treatment of a course in modern higher algebra. A student of physics who possesses mathematical maturity should find it possible to obtain a good introduction to the theory of matrices from this book, even though his formal training in algebra has been confined to the ordinary first course in college algebra.

Fourier Series and Boundary Value Problems. Ruel V. Churchill, Associate Professor of Mathematics, University of Michigan. 216 p., 15×23 cm. *McGraw-Hill*, $2.50. Designed for students of physics, engineering and mathematics who have had an introductory course in ordinary differential equations and one semester of advanced calculus, this introductory textbook on Fourier series and their applications seeks, first, to equip the student with that part of the theory of orthogonal sets of functions which is essential to the usual applications arising in physical science; and, second, to give him a thorough knowledge of the classical process of solving boundary value problems in partial differential equations with the aid of those expansions in series of orthogonal functions. The book is the outgrowth of a course which the author has given for many years at the University of Michigan.

The Modern Theory of Solids. Frederick Seitz, Assistant Professor of Physics, University of Pennsylvania. 713 p., many diagrams, 87 tables, 15×23 cm. *McGraw-Hill*, $7. This extensive and unified treatment of the theory of all types of crystalline solids is intended for the use of students and experimentalists in physics and chemistry, of engineers and metallurgists with a mathematical bent, and of theoretical physicists who are interested in the electron structures of solid bodies. For the purpose at hand, the author has classified solids as metals, ionic crystals, valence crystals, semi-conductors and molecular crystals. These five types are described in the opening chapter and are treated in succeeding chapters under the following headings: Classical theory of ionic crystals; Specific heats of simple solids; Free-electron theory of metals and semi-conductors; Quantum-mechanical foundations; Approximate treatment of the many-bodied problem; Molecular binding; The band approximation; Approximate methods; Cohesive energy; Work function and the surface barrier; Excited electronic states of solids; Electronic structure of the five solid types; Dynamics of nuclear motion; Theory of conductivity; Magnetic properties; Optical properties. Numerous topics that involve mathematical details of interest mainly to the theoretical physicist are plainly marked and the reader may omit them if he desires. This book is one of the McGraw-Hill *International Series in Physics*, of which Professor Lee DuBridge is consulting editor. Now comprising some 30 volumes, this series was issued under the general editorship of the late Professor F. K. Richtmyer from its inception in 1929 until his death in 1939.

Introduction to Physical Optics. John Kellock Robertson, Professor of Physics, Queen's University (Canada). 522 p., 230 figs. and plates, 15 tables, 14×22 cm. *Van Nostrand*, $4. Although not differing in general character from the editions of 1929 and 1935 [Am. J. Phys. **4**, 46 (1936)], this well-known textbook now has added to it some much-needed material on the microscope and on the uses, advantages and disadvantages of Polaroid. The author has also adopted some of the recommendations in the report of the committee on the teaching of geometrical optics of the American Association of Physics Teachers [Am. J. Phys. **6**, 78 (1938)].

Advanced Electrical Measurements. Walter C. Michels, Associate Professor of Physics, Bryn Mawr College. Ed. 2. 357 p., 155 figs., 14×22 cm. *Van Nostrand*, $3.50. Appearing first in 1932 under the joint authorship of William R. Smythe and the present author, this manual has now been thoroughly revised so as to include, especially, new applications of electronic methods to electrical measurements and new networks for alternating current impedance measurements. The general scope and purposes of the original edition are preserved; namely, to provide detailed experimental directions and brief discussions of the theory of the standard methods and apparatus of the electrical measurements laboratory, and of important applications of electrical instruments in thermometry, vacuum technics and electrochemistry.

Photography

Making Your Photographs Effective. J. A. Lucas and Beverly Dudley. 385 p., 189 figs., 17 tables, 15×23 cm. *McGraw-Hill*, $5. Unlike the conventional work on the photographic process, this book emphasizes the methods used to obtain special photographic effects for advertising purposes. Many examples of such photographs are shown, together with detailed descriptions of the lighting, arrangement of subject matter, montage and multiple printing technics employed in each case. The photographic equipment, exposure and development are also described. That portion of the book devoted to basic processes contains a wealth of immediately useful material. Although the book is not suitable for a college textbook and, indeed, was not written with that end in view, it should serve to give the physicist pressed into service as instructor in an elementary photography course an insight into commercial photographic methods.—W. W.

Fundamentals of Photography. Paul E. Boucher, Professor of Physics, The Colorado College. 356 p., 89 figs., 11 tables, 16×23 cm. *Van Nostrand*, $3. The preparation of a textbook in elementary college photography is complicated by the wide variation among courses offered in semester-hours, prerequisites, and emphasis placed upon the theory and practice. In this book for a one-semester course, Professor Boucher has succeeded in avoiding oversimplification on the one hand and the overextension arising out of a desire to produce a complete treatise on the other. While pictorial composition has been somewhat neglected, the choice of subject matter is otherwise admirably suited to this type of course. The expositions of many of the topics ordinarily found difficult by the nonscience student are enriched by the inclusion of experimental data obtained with common laboratory equipment. The balance maintained between photographic theory and photographic technic is such as to make the book valuable both in the lecture room and the laboratory. The 17 laboratory exercises are arranged in the order in which the topics are discussed in the text. The appendix includes a formulary and glossary of photographic terms.—W. W.

Photographic Exposure. P. K. Turner. 146 p., 14 tables, 59 figs., 12×19 cm. *Pitman*, $1.75. The numerous complicating factors in the photographic exposure problem are described in the first five chapters. In the sixth chapter these factors are related in the exposure equation, $T=3N^2E/SR$, where T is the exposure time in seconds, N is the f-number, E is the exposure required in lux-seconds, S is the illumination on the subject in lux and R is the reflection factor of the subject. The remainder of the book is devoted to a description of the manner in which the exposure equation is solved with the aid of tables, calculators and meters ranging from the Watkins meter of the 1890's to the latest photoelectric types. The author presents the advantages and limitations of each and discusses the technic of using some of the modern meters for best results. Some useful data on shutters, film-speed rating scales, exposure factors for moving objects and "close-ups," photographic light sources, etc., are included in an appendix. Numerical examples are employed throughout to illustrate the manner in which the terms in the exposure equation may be evaluated for the solution of common photographic problems. Though the subject matter of this book is covered somewhat more fully in the *Handbook of Photography* [Am. J. Phys. **8**, 269 (1940)], Mr. Turner's treatment is to be commended for its organization and for the emphasis it places on exposure as the heart of the photographic process.—W. W.

Electrical Engineering

Mathematics Applied to Electrical Engineering. A. G. Warren, Research Department, Woolwich. 399 p., 131 figs., 14×22 cm. *Van Nostrand*, $4.50. This book provides a comprehensive and very thorough review of the mathematics most needed by the student and practicing electrical engineer. In choosing the material to be included, the author was guided by his own needs during some thirty years' experience in engineering education and research.

Experimental Electrical Engineering. Vol. II. Vladimir Karapetoff, Emeritus Professor of Electrical Engineering, Cornell University, and Boyd C. Dennison, Professor of Electrical Engineering, Carnegie Institute of Technology. Ed. 4. 846 p., 498 figs., 15×23 cm. *Wiley*, $7.50. Appearing first in 1907 and then in later editions under the authorship of Professor Karapetoff, this two-volume textbook for engineers and for students in engineering laboratories has now been completely revised and reset. Volume II furnishes a more advanced study of certain subjects introduced in Volume I and, in addition, includes material on a.c. bridges, single-phase and polyphase commutator machines, mercury-arc rectifiers, transmission lines, magnetic contactor control, oscillographs, electronic devices, wave analysis and high frequency measurements. The volume also includes directions for 163 experiments, these being distributed throughout the text so as to form an integral part of it.

Motion Picture Films

Sun and Moon. 16 mm sound or silent. 11 min. *Bell & Howard Filmo-Sound Library* (1801 Larchmont Ave., Chicago), rental or sale. Astronomical photography rather than diagrams.

Elements of Photography. 16 mm silent. 22 min. *Walter O. Gutlohn.* (35 W. 45th St., New York), rental or sale. All the steps in taking, developing and printing a picture are shown in detail; the procedure is based on the training methods of the Army Signal Corps.

Tomorrow's Railroads. 16 mm sound. 13 min. *Waugh Equipment Co.* (420 Lexington Ave., New York), loaned gratis. Maintenance and operation of modern passenger trains; developmental work to improve their riding quality.

Nickel Refining. 16 mm sound. 11 min. *Bureau of Mines* (4800 Forbes St., Pittsburgh), loaned gratis. Shows the successive processes in a large refinery producing electrolytic nickel, black nickel oxide and nickel shot. Other films in the series are "Nickel Mining" (16 min) and "Nickel Milling and Smelting" (17 min).

Report of the Secretary of the American Association of Physics Teachers

THE executive committee of the American Association of Physics Teachers held two meetings at the University of Pennsylvania on December 27 and 29, 1940. Members present were R. M. Sutton, presiding; A. G. Worthing, P. E. Klopsteg, T. D. Cope, A. D. Hummel, Louise McDowell, D. Roller, W. H. Michener, K. Lark-Horovitz and W. B. Pietenpol. Other members of the Association present by invitation were H. A. Barton, L. I. Bockstahler, T. B. Brown, H. L. Dodge, R. C. Gibbs, G. R. Harrison and F. Palmer.

Upon the recommendation of the committee on a memorial for the late Professor Richtmyer, of which P. E. Klopsteg was chairman, it was voted that an annual memorial lecture at the Christmas meetings be established under the direction of a standing committee of the Association, that not more than $100 per year be appropriated for the next three years to defray the expenses of the lecture, and that the committee on the lectureship be asked to seek an endowment for maintaining the memorial after 1943. After hearing the report of the committee on fellows and members emeritus, which was presented by A. G. Worthing, chairman, the executive committee (*a*) recorded its disapproval of the idea of establishing the grade of *fellow*, and (*b*) directed that a recommendation concerning the establishment of the grade of *member emeritus* be presented at the annual business meeting. The committee on the training of physicists for industry, P. I. Wold, chairman, reported that circumstances connected with the National Defense program made further work by this committee not particularly useful at this time. W. H. Michener reported for the nominating committee of 1940. These four committees were discharged with a vote of thanks for their services.

The following committees and chairmen, from which reports were also received, will continue work during 1941: Membership, R. C. Gibbs; Concerted action with other groups in regard to science in secondary schools, K. Lark-Horovitz; Physics in relation to medical education, W. E. Chamberlain; Tests and testing, C. J. Lapp; Terminology, D. Roller; Symbols and abbreviations, H. K. Hughes; Awards, R. M. Sutton. The secretary stated that all seven regional chapters had submitted reports covering their activities in 1940.

R. H. Howe, R. Morgan and G. E. Owen were appointed as tellers for the 1940 election; and L. I. Bockstahler, F. L. Brown and J. W. Broxon, as members of the nominating committee for 1941. R. M. Sutton was chosen to serve for a three-year period as representative of the Association before the American Council on Education, replacing A. W. Smith. A committee on National Defense was established, consisting of E. C. Kemble, chairman, F. L. Bishop, P. E. Klopsteg, R. A. Patterson and G. R. Harrison.

A. G. Worthing was nominated to succeed F. Palmer as representative of the Association on the governing board of the American Institute of Physics. A vote of thanks was extended to the Institute for its generosity in paying the annual dues of the Association, $100, as a constituent member of the American Council on Education. It was voted that the financial support which the Association gives the Institute be continued at the increased rate of 20 percent in 1941, provided the other four constituent societies of the Institute take similar action. H. A. Barton reported that "On the initiative of the Institute, a grant of $20,000 has been received from the Rockefeller Foundation to compensate the journals during the years 1940–41" for loss of income due to circumstances created by the war.

Upon recommendation of the editor, P. Kirkpatrick, T. H. Osgood and F. G. Slack were appointed associate editors of the AMERICAN JOURNAL OF PHYSICS for the period 1941–1943. It was agreed that general attention should be drawn to the provision of the By-Laws which gives the Association prior rights of publication of all papers read before it, and to the rule that contributed papers by nonmembers be introduced by members.

The treasurer was authorized to reinstate former members of the Association upon payment of dues for the current year, and to accept Canadian funds at par in payment of dues. The secretary was directed to convey to the International Cancer Research Foundation an expression of appreciation for its generosity in meeting the expenses of one of the invited speakers at the Philadelphia meeting.

It was voted that the Association meet with the Pacific Division, A.A.A.S., at Pasadena, California, in June, 1941; E. C. Watson was appointed chairman of the committee on arrangements.

The Annual Business Meeting.—The annual business meeting, held at the Drexel Institute of Technology, was called to order by President Sutton at 9:30 A.M., December 30, 1940. Fifty members were present.

The annual report of the treasurer [Am. J. Phys. 9, 59 (1941)] was presented and adopted without dissent. The actions taken by the executive committee at its meetings on December 27 and 29 were reviewed by the secretary. On behalf of this committee, the secretary placed Benjamin H. Brown, Oersted medallist for 1939, in nomination for honorary membership; he was elected without dissent.

It was voted that *By-Laws I. Dues.* (*1*) be amended by adding: "Members of at least ten years standing who have reached the age of sixty and have retired from active teaching may, at their request, be given emeritus status and relieved from payment of dues. They will retain all privileges of members except that of receiving the journal.

R. Morgan reported for the tellers that the results of the election of officers for 1941 were as follows:

President: A. G. WORTHING.
Vice President: A. A. Knowlton.
Treasurer (two years): PAUL E. KLOPSTEG.
Secretary (two years): THOMAS D. COPE.
Members of the Executive Committee (two years): C. J. LAPP, FRANCIS G. SLACK.

Under new business, M. N. States and L. E. Smith called attention to developing opportunities for physicists in secondary education, and R. A. Patterson spoke of the work of physicists on National Defense projects at many institutions. The meeting adjourned at 10:20 A.M.

THOMAS D. COPE, *Secretary*

DIGEST OF PERIODICAL LITERATURE

Apparatus and Demonstrations

Cleaning benches. W. A. Becker; *J. Chem. Ed.* **17**, 595 (1940). After the top of a laboratory table has been washed clean of residues and stains, dry it with a rubber window squeegee instead of a sponge. The process is rapid and the dried top will not have a spotty appearance.—D. R.

Simplifying electrical connections. J. W. Davis; *Sch. Sci. Rev.* **22**, 221–223 (1940). Six receptacles are fastened in line to a board, which is mounted on rubber feet to prevent slipping. The first three receptacles are connected in parallel and the others in series. Lengths of lamp cord provided with two-prong plugs are used to connect lamps meters, etc., to the power supply through the board. Plugs whose terminals are connected together can be used to short one or two of the series receptacles as needed.—J. D. E.

Dufay color film as a diffraction grating. J. N. Emery; *Sch. Sci. Rev.* **22**, 223 (1940). The *réseau* of Dufay film consists of alternate blue and green lines, crossed at right angles by red lines; thus it forms a combined filter and grating, with 200 lines/cm. A piece of film is cleaned of emulsion in potassium cyanide solution, washed, dried and cut into 1-cm squares. The squares are mounted between glass plates, with the lines parallel to the edges of the plates. A piece of black paper with a 7-mm hole is used as a mask. A double slit is made by ruling two fine parallel lines 1 cm apart on a lantern slide plate. When the grating is held close to the eye and the double slit is viewed through it, a series of bright spectra of the first three or four orders is seen on each side of each slit. By moving the slit to and fro, the corresponding images are made to coincide in the middle, and the distance from the slit to the film is measured. Then the wave-length of the light transmitted by the film can be calculated from the equation $\lambda=(a/n)\sin\alpha_n=as/2dn$, where a is the grating space (0.005 cm), α_n is the diffraction angle of the nth order, s is the separation of the lines of the double slit, and d is the distance from slit to film. The wave-lengths transmitted by the red and green portions of the film are about 6450 and 5520A, respectively.—J. D. E.

Lecture demonstrations of Boyle's law and of change of state. F. B. Dutton; *J. Chem. Ed.* **18**, 15–17 (1940). For a simple, easily visible demonstration of Boyle's law, fit four 1-l flasks with two-hole rubber stoppers, wire them in place, and connect the flasks to one another and to an open-tube mercury manometer by means of 7-mm glass tubing (Fig. 1). Have each interval on the manometer scale represent $\frac{1}{3}$ atm. In use: (1) evacuate the system with a pump connected at P, thus demonstrating atmospheric pressure; (2) readmit air, there now being 4 l of air under a pressure of 1 atm; (3) connect P to the water supply and admit water until flask *4* is full (Fig. 1), there now being 3 l of air under a pressure of $1\frac{1}{3}$ atm; (4) admit

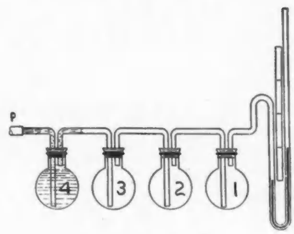

Fig. 1. Boyle's law.

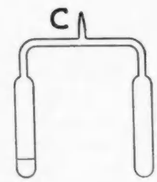

Fig. 2. Change of state

more water until flask *3* also is full, the volume of air then being 2 l and the pressure, 2 atm. It is not advisable to attempt to fill flask *2*. To vary the experiment, start with a pressure of $\frac{1}{2}$ atm in the four flasks. Point out that a more precise experiment would involve corrections for the volume of tubing, calibration of flasks and partial pressure of water vapor; and would show departures from the ideal gas law.

The modified cryophorous in Fig. 2 affords a simple and ready demonstration of change in state. From 1-in. test tubes draw down two ampoules and connect them by a 7-mm glass tube having a side tube sealed in at C. Introduce about 20 ml of ether at C, distribute it equally between the two ampoules, and partially evacuate the system. After the ether has boiled violently for 1 min, thus sweeping out the air, close the rubber connection to the pump with a screw clamp and seal off the side tube. In use, pour all the ether into one ampoule and surround the other ampoule by liquid air or by acetone and dry ice. Frost will form on the outside of the ampoule containing the ether.—D. R.

Check List of Periodical Literature

Trend in weapon types and design. E. McFarland; *J. Frank. Inst.* **230**, 413–432 (1940). The author is a brigadier-general in the Ordnance Department, U. S. Army.

The steam locomotive: its development and present position in railroad transportation. L. H. Fry; *J. Frank. Inst.* **230**, 529–565 (1940).

Science in general education at the college level. L. W. Taylor; *Sci. Ed.* **24**, 241–249 (1940).

Science education in the business curriculum. M. Winokur; *Sci. Ed.* **24**, 256–260 (1940).

Life, entropy and Maxwell's demon. R. E. D. Clark; *Sch. Sci. Rev.* **21**, 1117–1131 (1940). Conclusion (with references) of the article "Entropy and the universe"

[see Am. J. Phys. **8**, 206 (1940)]. "At the end of half a century of criticism and misunderstanding, the Maxwellian 'demon' has emerged unscathed. . . . It is not the 'demon' but we ourselves who are able to watch the movements of a large number of objects and sort them out, with a view to a performed plan, against all the rules of nature and of chance. . . . It is our minds which, at every turn, violate the cherished basis of all our science, the law of morpholysis."

Types of physics courses now in use in pre-engineering schools. L. W. Jones; *J. Eng. Ed.* **31**, 225–228 (1940).

Reflectors used in highway signs and warning signals. G. A. Van Lear, Jr.; *J. Opt. Soc. Am.* **30**, 462–487 (1940).

The tragedy of Rudolf Diesel. H. Crew; *Sci. Mo.* **51**, 512–523 (1940). A well-written and exceptionally interesting account of the essential facts in the life and character of Diesel, as set forth in his son's volume, *Diesel, der Mensch, das Werk, das Shicksal* (1939).

Physics in the rubber industry. J. W. Schade, S. H. Hahn, O. R. Fouts, J. E. Field, W. C. Sears, H. Marks, J. N. Street, J. H. Dillon; *J. App. Phys.* **12**, 1–54 (1941). Seven papers on the properties of rubber and on physical problems involved in its manufacture and use.

Effusion apparatus for demonstration of Graham's law. C. R. Johnson, J. P. Finfrock; *Sch. Sci. and Math.* **41**, 18–20 (1941). The apparatus is inexpensive and affords quantitative results.

Amateur telescope-making. J. L. Russell; *Sch. Sci. and Math.* **41**, 63–68 (1941). Helpful suggestions, with many references to the literature and to sources of supplies. "No one . . . need be without his own telescope."

Amateur scientists and their organizations. W. S. Thomas; *Sci. Mo.* **52**, 68–78 (1941).

Searching the literature of science. E. L. Jones; *J. Sci. Inst.* **17**, 253–257 (1940). Principles and procedures for extracting information from the literature of a science.

Chemistry instruction for purposes of general education. L. W. Taylor, L. M. Heil, P. E. Schaefer; *J. Chem. Ed.* **18**, 10–14 (1941). For the companion report on physics, by the same committee, see *Am. J. Phys.* **8**, 49 (1940).

Notes on the care and maintenance of Variacs. H. H. Dawes; *Gen. Radio Exp.* **15**, 6–8 (1941).

Some famous balances. R. E. Oesper; *J. Chem. Ed.* **17**, 312–323 (1940). The article includes photographs of balances made famous either because of the men who used them or because of their use in outstanding researches.

Photography in the college curriculum. J. D. Schumacher; *J. Chem. Ed.* **17**, 427–429 (1940).

Thomas Russell Wilkins, 1891–1940

VERY suddenly and apparently with no warning whatsoever, Dr. T. Russell Wilkins suffered a heart attack and died on December 10, 1940, while walking back to his laboratory after luncheon. Some years ago he had an apparently serious heart condition which he told me resulted from overexertion in 1917–18 when, as a member of the U. S. Signal Corp, he was conducting experiments with falling balloons in the elevator shaft of the Washington Monument. However, he seemed to have entirely recovered from this condition and in recent years had not spared himself either from physical exercise or from long hours of work in his laboratory.

Doctor Wilkins was born in Toronto, Canada, in 1891. He received the bachelor's degree from McMasters University in 1912 and the doctorate from the University of Chicago in 1921. From 1918 to 1925 he was Professor of Physics at Brandon College, Canada. The year 1925–1926 he spent in Rutherford's laboratory at Cambridge. He became Professor of Physics at the University of Rochester in 1926, and from 1929 to 1939 was acting director of its newly organized Institute of Optics. He was married in 1913 to Olive Cross. She died in 1937, and recently he was married to Gwen Whidden, daughter of President Whidden of McMasters.

Following his work with Rutherford he came to Rochester eager to pursue several lines of pioneering research in the field of radioactivity, particularly in connection with the actinium series, and during the remainder of his life this field claimed his chief interest. When he inaugurated his program he felt that this was a field too much neglected by physicists and yet of the highest importance in the development of modern physics. Very early he became interested in the possibilities of photographic emulsions as a means of recording and investigating radioactive emanations. The development of this technic and of a clever camera to use it constitutes one of his most important contributions to research, not only in radioactivity, but also in the field of cosmic rays, nuclear disintegration and general atomic structure. For this work he received the 1939 medal of the Royal Photographic Society. At the time of his death he was busily engaged in further study of a phase of inelastic scattering of protons which he had observed while examining proton tracks in his special photographic emulsion. He recently received a special grant-in-aid from the Society of Sigma Xi for the advancement of his research. In this work on elastic scattering of protons he was collaborating with Dr. Gerald Wrenshall. of McMasters University, who is now collecting Doctor Wilkins' unpublished data and will publish it soon.

Russell Wilkins had the spirit of a pioneer and a remarkably resourceful mind, with the result that he was happy in his work; he was unusually energetic, and his enthusiasm too often, perhaps, carried him beyond his physical strength. He was companionable, and possessed great personal charm and culture; his ready wit, keen humor and sympathetic nature gained for him a wide circle of friends both within the University and outside. To his friends he was loyal, as he was to the University and to any cause in which he became interested. It is with sincere regret that we must record his passing.

Floyd C. Fairbanks